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SITE INDEX SYSTEMS FOR MAJOR YOUNG-GROWTH FOREST AND WOODLAND SPECIES IN NORTHERN CALIFORNIA

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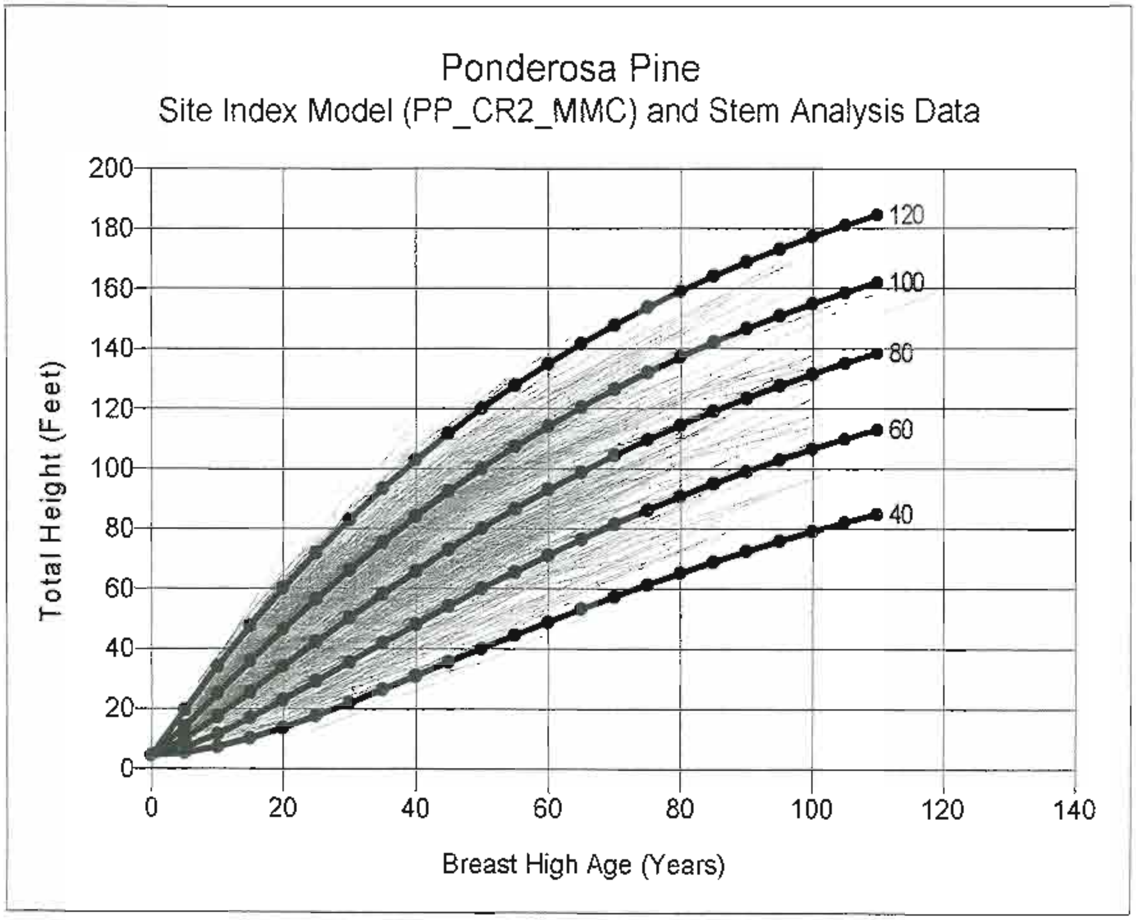

Abstract

Young-growth base age invariant site index models were developed for eleven conifer and five hardwood species found in Northern California (redwood, coastal Douglas-fir, grand fir, ponderosa pine, interior Douglas-fir, sugar pine, white fir, red fir, incense-cedar, Jeffrey pine, lodgepole pine, tanoak, black oak, madrone, red alder, and California laurel). In addition, composite site index models were developed for other true oaks and selected groups of interior conifers. Unbiased parameter estimation procedures were employed requiring a simultaneous estimation of all tree reference-heights that appear as independent variables along with global parameters of the site index model. Resulting site index models were compared and evaluated against existing ones, which produced a set of site index models considered to be the most accurate possible with current data availability. Intra-stand species site index correlations are developed, sampling properties of different site tree selection rules are evaluated, and a young-growth site class basis is proposed for different regions of the State.

Key Words: Site index, site productivity, base-age invariance, young-growth site index models, site class systems.

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Site Index Systems for Major Young-Growth Forest and Woodland Species in Northern California

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Contributors

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1. Introduction

Site index, the average total height of a specified upper canopy stand component at an arbitrary base age, has evolved into a de facto standard for rating the productive capacity of timber stands. In California, early uses of site index were primarily as a means to access normal yield tables and site class volume tables (Dunning, 1942). In modem times, site index has grown to be a multi-purpose forest measure. It is used in forestland taxation and appraisal, regulatory compliance under the California forest practice rules (CFPR), rating treatment opportunities, growth and yield forecasting, other forms of vegetation research, and a variety of related topics.

Over the last 80 years, more than twenty site index models have seen some form of service in California (Table 1.1). These models have been borrowed from nearby regions or developed specifically for individual species or groups of species within the State. While seeming to comprise an extensive knowledge base, there are several problems with existing site index models that limit the effectiveness of the concept in contemporary young-growth forest management applications in the State.

The majority of existing site index models applied in California were developed by traditional anamorphic guide curve techniques (Bruce, 1926) using single height/age samples on individual trees or plot averages. These types of models are known a priori to be potentially biased largely due to the distinct possibility that site index may be correlated with age in the sample (Monserud, 1984; King, 1966). The guide curves of McArdle and Meyer (1961) and Dunning (1942) for example, are deeply entrenched in site index usage in the State. These curves were the site basis for early soil-vegetation and vegetation type maps. They were the apparent origins of the common site I – V vernacular used in California, and they still remain a regulatory statute in the forest practice rules. Available evidence however, suggests that they are biased for young-growth site determination within the State (Wensel and Krumland, 1986; Powers, 1972a). Methods employing stem analysis and other forms of repeated measures on individual trees are generally considered to be superior, unbiased and produce a more accurate assessment of dominant height growth development (Curtis, 1964).

Age usage applied in California site index models is by no means uniform and inhibits meaningful comparisons and standardization. Most combinations of traditional site index base ages (50, 100 and 300 years) and age bases (total age, breast-high age) are found. Difference in age basis alone can often result in site index differences of 10 to 30 feet for the same stand depending on how long it takes for trees to reach breast height. Conversions between age bases are at best arbitrary and can often be a significant source of inaccuracy in estimating site index for specific stands.

Table 1.1. Existing Site Index Models used in California.

Conifers		
Species	**Source**	**Description**
Douglas-fir	Schumacher, 1930	Anamorphic guide curves based on single height/age data pairs. Developed in conjunction with a normal yield study of the entire range of Douglas-fir in California. Seldom used.
Douglas-fir	King, 1966	Polymorphic site index model based on stem analysis data. Sample data collected in western Oregon and Washington. Generally considered to be one of the best Douglas-fir site curves in the Pacific Northwest. Site classification basis for CRYPTOS.
Douglas-fir	McArdle and Meyer, 1961	Anamorphic guide curves based on single height/age data pairs. Developed in conjunction with a normal yield study of Douglas-fir in the Pacific Northwest. CFPR official Douglas-fir site classification basis for the coast region. Also used as a site classification basis for early soil – vegetation surveys in coastal California..
Incense-cedar	Dolph, 1983	Site prediction model based on Dahms' (1975) method and constructed with the LDMC stem analysis data set. Samples were primarily from National Forest land on the west slope of the Sierra Nevada mountains. Site classification basis for the Klamath Mountains version of FVS.
Mixed-conifer	Dunning & Reineke1933	Anamorphic guide curves based on single height/age data pairs. Developed in conjunction with an empirical yield study of young growth mixed conifer stands in the Sierra California. Occasionally used in research studies.
Mixed-conifer	Dunning, 1942	Anamorphic guide curves based on single height/age data pairs. Developed for old growth selection forests in the Sierra Nevada mountains. Site index source for early inland soil -vegetation maps. CFPR official site classification basis for interior mixed conifer forests.
Mixed-conifer	Biging and Wensel, 1985	Polymorphic site index model based on the NCStem stem analysis data set. Site classification basis for CACTOS.
Mixed-conifer	Biging, 1984	Methodological extension of Biging and Wensel's (1985) site index model.
Ponderosa pine	Powers and Oliver, 1978	Polymorphic site index model base on the POPP stem analysis data set. Sampling locations spanned most of the native range of ponderosa pine in Northern California.
Ponderosa pine	Barrett, 1978	Polymorphic site prediction model based on Dahms' (1975) method. Sample locations on National forest land in eastern Oregon and Washington. Sometimes used for east side pine types in California.
Ponderosa pine	Arvanitis, Lindquist, and Palley 1964	Anamorphic site index model based on single height/age data pairs. Samples collected from the west slope of the Sierra Nevada mountains. Seldom used.
Ponderosa pine	Meyer, 1938, 1961	Anamorphic guide curves based on single height/age data pairs. Developed in conjunction with a regional normal yield study of ponderosa pine in the western United States.
Redwood	Bruce, 1923	Anamorphic site index model based on single height/age data pairs. Developed in conjunction with a normal yield

		study for the entire range of young growth coastal redwood. The first site index system for California. Seldom used.
Redwood	Lindquist and Palley, 1961	Guide curves used with empirical yield tables for young growth redwood. Official CFPR redwood site classification basis for the coast region. Also used for some soil-vegetation map site classifications.
Redwood	Wensel and Krumland, 1986	Polymorphic site curves based on stem analysis and repeated site tree measurement from growth plots. Site classification basis for CRYPTOS
Red fir	Schumacher, 1928	Anamorphic guide curves based on single height/age data pairs. Developed in conjunction with a normal yield study of red fir in California. Seldom used.
Red fir	Dolph, 1991	Polymorphic site index curves derived from the LDRF stem analysis data set. Site classification basis for the Klamath Mountains version of FVS.
White fir	Schumacher, 1926	Anamorphic guide based on single height/age data pairs. Developed in conjunction with a normal yield study of white fir in California. Seldom used.
White fir	Dolph, 1987	Site prediction model based on Dahms (1975) method and constructed with the LDMC stem analysis data set. Samples were primarily from National Forest land on the west slope of the Sierras. Site classification basis for the Klamath Mountains version of FVS.
Hardwoods		
Black oak	Powers, 1972b	Polymorphic site index curves for unmanaged stands of black oak. Sampling locations were PSW experimental forests on the west slope of the Sierras and the Southern Cascades.
Madrone Red alder Tanoak	Porter and Wiant, 1965	Anamorphic site index curves based on stem analysis. Sampling was performed in Del Norte and Humboldt counties and consisted of 25-30 trees for each species. Red alder curves were found to be almost identical to those of Johnson and Worthington (1963) for red alder in the Pacific Northwest.
Coast live oak Blue oak	Delasaux and Pillsbury, 1987	Site prediction model based on Dahms' (1975) method. Stem analysis data from approximately 25 plots of each species from Monterey and San Luis Obispo counties.

Similarly, sample selection recommendations for determining site index are varied. Recommendations proposed by authors of the site index studies in Table 1.1 include: a) a random sample of dominant and co-dominant trees; b) average height and age of dominant and co-dominant trees of mean quadratic DBH, c) largest 10 of 50 trees by DBH; d) a random selection of dominants; e) tallest tree in the stand; f) one tree with the highest site index. Many field foresters have some subjective 'inherent' notion of what an appropriate site tree is. Unfortunately, they are not all the same. While selection procedures may be of minor importance, a lack of a commonly accepted statewide basis can have serious impacts on the usefulness of any applied research where site index is an explanatory variable.

The range of commercial forest species in California is extensive, spanning seven major ecological sections (Miles and Goudey, 1997: see Figure 1.1), each with its own unique geomorphologic origins and mesoclimate. These ecological sections will be used as the basis for differentiating site curves by geographical region in this study. As Powers (1972a) succinctly notes, 'Climate, geology and time induced such racial and edaphic variability that reliance on a single set of site curves for a particular species seems tenuous'. While different site curves for interior and coastal Douglas-fir have traditionally been used, the possibility that site curves may vary by geographical region for other species groups has been largely unexplored.

Species considered components of mixed conifer stands have broad distributions within the State. Dunning and Reineke (1933) noted that, at a given stand total age, total heights of dominant ponderosa pine[1], Douglas-fir, white fir, and red fir were virtually the same and could be used interchangeably for determining mixed conifer site index. Biging (1984) and Biging and Wensel (1985) have also developed 50-year breast-high age mixed conifer site index models for the same species as Dunning and Reineke with the addition of sugar pine and incense cedar. Four other recent stem analysis based site index models have been developed for specific mixed conifer species within the State. Dolph (1983, 1987, 1991) developed 50-year breast-high age basis models for incense cedar, white fir and red fir. Powers and Oliver (1978) have developed a 50-year total age base site index model for ponderosa pine under stocking control. Height predictions of all of these models based on selected heights at a common breast-high age of 20 years are shown in Figure 1.2. Dunning's, Dunning and Reineke's, and Powers and Oliver's curves have been 'adjusted' to a breast-high age basis for expository purposes (methods are detailed in chapter 5). It is not clear whether the differences shown in Figure 1.2. reflect sampling variation, differences in analytical construction methods, or indicate that there are significant differences in the height growth patterns of individual mixed conifer species. In any event, a clearly defined mixed conifer site index system is incomplete and a systematic appraisal would be highly beneficial.

In general, there are problems in the application of the site index concept in California that affect its precision and usefulness as a forest management tool. Clearly, a consolidation of the site index knowledge base would be of practical benefit in applications.

1.1 Study Objectives

The primary purpose of this study is to achieve several interrelated objectives:

1. Provide the best set of contemporary young-growth site index models for major conifer and hardwood species in the State with consistent age basis and base age definitions. This set will be refined by regional and environmental factors as much as possible within the limits of available data. This set will be based on new models developed in the course of this study or recommendations based on evaluations of existing site index models.

2. Develop intra-stand site prediction models for different species so the site indices of unsampled species can be estimated from species whose site index has been estimated from sampling.

[1] Scientific names of all species mentioned in this study are shown in Table 1.2.

3. Evaluate site tree sample selection rules and propose recommendations that provide the most consistent and stable basis for a stand site index definition.

4. Propose a general young growth site classification (I-V) basis for different regions in the State with a common 50-year breast-high index age basis.

This study is synthetic in nature, relying on existing sources of data. With the exception of the hardwood data of Porter and Wiant (1965), virtually all of the data used in the development of existing stem analysis based site index models have been made available for this study. Over 2000 additional stem analysis records not used in the construction of existing site index models have also been assimilated for analysis. This database is also supplemented with the repeated long-term measurements of over 10,000 site trees from forest growth and continuous forest inventory (CFI) plots.

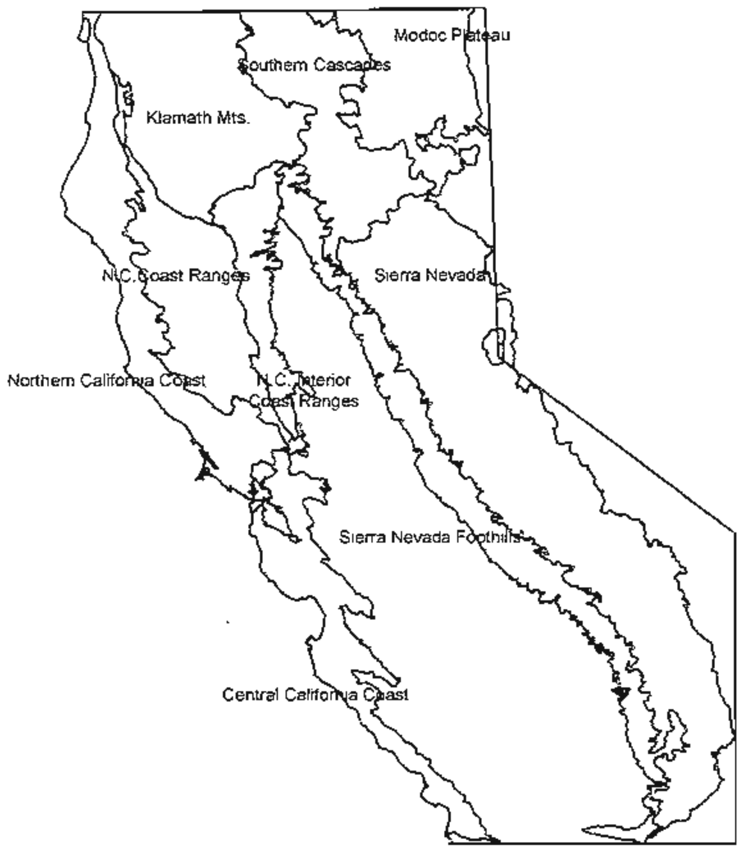

Figure 1.1. *Ecological sections in California used in this study (Miles and Goudey, 1994).*

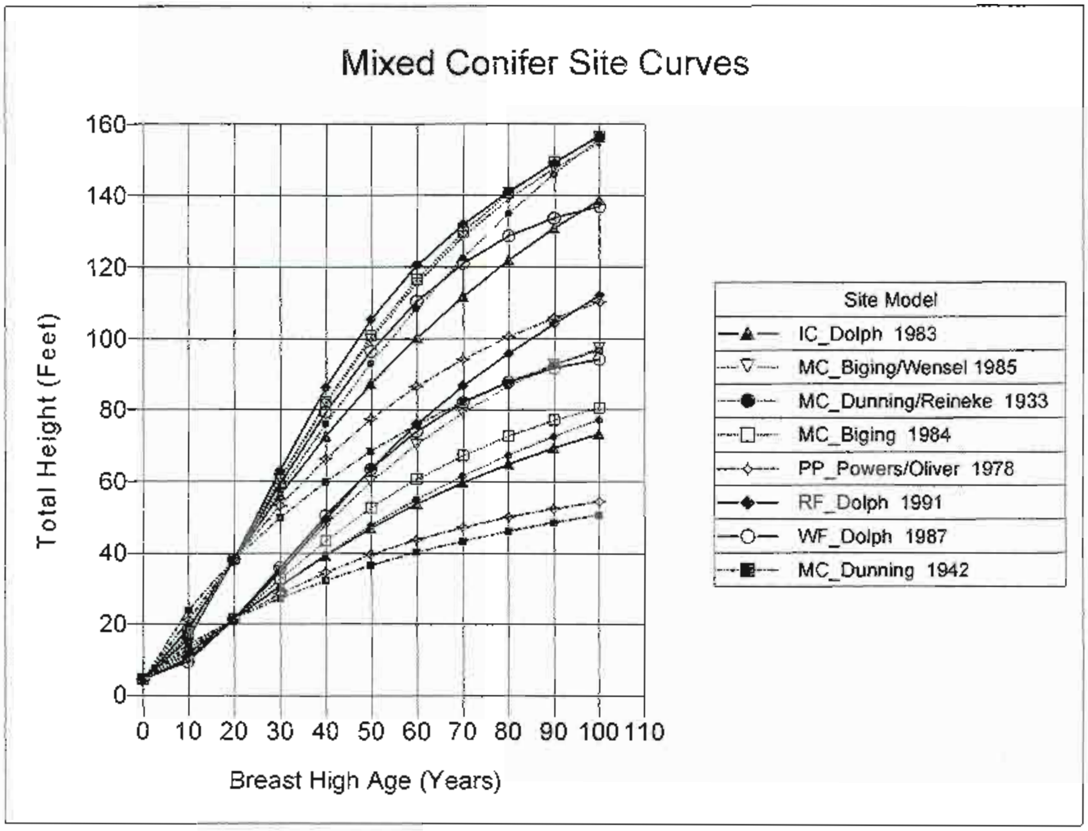

Figure 1.2. *Existing site index curves for mixed conifer species for a common initial age of 20 years at selected site indices.*

Table 1.2. Common and scientific names of California species.

COMMON NAME	SCIENTIFIC NAME	Species Code
White fir	Abies concolor [Gord. & Glend.] Lindl.	WF
Grand fir	Abies grandis [Dougl] Lindl.	GF
Red fir	Abies magnifica [A] Murr.	RF
Incense cedar	Libocedrus decurrens Torr.	IC
Sitka spruce	Picea sitchensis [Bong.] Carr.	SS
Knobcone pine	Pinus attenuata Lemm.	KP
Jeffrey pine	Pinus jeffreyii Grev. & Balf.	JP
Sugar pine	Pinus lambertiana Dougl.	SP
Bishop pine	Pinus muricata D. Don.	BP
Ponderosa pine	Pinus ponderosa Laws.	PP
California foothill pine	Pinus sabiniana Dougl.	DP
Douglas-fir	Pseudotsuga menziesii [Mirb.] Franco	DF
Redwood	Sequoia sempervirens [D. Don] Endl.	RW
Western redcedar	Thuja plicata Donn	RC
Western hemlock	Tsuga heterophylla [Raf.] Sarg.	WH
Mountain hemlock	Tsuga mertensiana [Bong.] Carr	MH
Bigleaf maple	Acer macrophyllum Pursh.	BM
Red alder	Alnus rubra Bong.	RA
Pacific madrone	Arbutus menziesii Pursh.	MD
Eucalyptus	Eucalyptus spp.	EU
Tanoak	Lithocarpus densiflorus [Hook. & Arn.] Rehd.	TO
Black cottonwood	Populus balsamifera ssp.trichocarpa	BC
California live oak	Quercus agrifolia Nee.	LO
Canyon live oak	Quercus chrysolepis Liebm.	CLO
Blue oak	Quercus douglasii [Hook. & Arn.]	BLO
Engelmann oak	Quercus engelmannii Greene.	EO
Oregon white oak	Quercus garryana Dougl.	OWO
California black oak	Quercus kelloggii Newb.	BO
Interior live oak	Quercus wislizenii A. DC.	ILO
California-laurel	Umbellularia californica [Hook. & Arn.] Nutt.	CL

2. Site Index Background

In this chapter, a brief overview of the site index concept is given and terms and concepts that will be used in the remainder of the study are introduced.

2.1 History and Basis

Young (1967) cites Evelyn's (1670) polemic work indicating qualitative references of site productivity date to at least the early Greeks and Romans. Roth (1916) however, attributes the formal quantitative origins of site evaluation to the Association of German Forest Experiment Stations in the late 1880's. This was the first time that a fairly large body of forestry professionals agreed on a common definition of site productivity. Between 1917 and 1922, several lively exchanges occurred in the United States on whether site productivity should be based on height/age relationships or mean annual increment of fully stocked stands (Bates, 1918; Frothingham, 1918; Roth, 1916, 1918; Watson, 1917). Total height was the winner and was adopted in 1923 by the Society of American Foresters as the official measure of site index (Chapman, 1923).

2.2 Stand Density and Site Index

Site index, as we know it today, is based on the primary assumption that the height development of upper canopy trees in even-aged stands is largely unaffected by stand density. Several authors have shown that height growth suffers in over stocked stands, primarily at early ages (Barrett, 1978; Oliver, 1972). Oliver and Larson (1996) also note that reduced growth is expected for trees with weak epinastic control in low-density situations. In managed situations however, this should not be a problem. In uneven-aged or selectively managed stands, trees are often spatially arranged in even-aged groups.

Scott et al. (1998) showed that height growth increased with stand density in young Douglas-fir plantations in the Pacific Northwest. No firm explanation was given. Flewelling et al. (2001) have subsequently constructed Douglas-fir site index curves with adjustments for stand density (trees per acre) and show a general increase in site index with increases in stand density. Part of this increase is probably definitional as they defined site index as the average height of the largest 40 trees/acre by DBH. As density increases, a fixed number of trees represents a smaller and smaller upper distributional percentage of the within-stand site index distribution. Thus, one would expect site index, if defined in this manner, to increase with density. In any event, refinements of this nature are beyond the scope of this study and will have to wait until a large documented database of plantation development is available for analysis.

2.3 Elements of Site Index Systems

After Wensel and Krumland (1986), site index systems are characterized by a) an age basis; b) a site index base age; c) a site index model; d) a stand component and sampling selection rule; and e) a site index prediction rule. Each of these features is discussed below.

2.3.1 Age Basis

Two general choices exist for a site index age basis: total age and breast-high age. Several total age definitions have been used including a) age since germination; b) age since planting; c) age since planting plus the age of the seedlings; d) age at stump height. Field determination of total age requires boring at ground level or else boring at breast height and making an 'adjustment'. Breast-high age (height 4.5 feet above ground level on the uphill side of a tree) is a more straightforward basis in site index systems as it conforms directly to the common field measuring point. Husch (1956) and others have found that the use of breast-high age rather than total age in fitting site index models to data results in more precise estimates as the variability due to early height growth (possible animal browsing, weed competition, etc.) are reduced. In this study, breast-high age will be used as the consistent age basis in site index systems.

Note that breast-high versus total age will in general produce higher site index estimates for comparable index ages. The difference is a left shift of each curve in a total age based system by the number of years required to reach breast height. For some species such as redwood and red alder, this difference is minor. Redwood sprouts can frequently reach breast height in a year. With other species, differences can be substantial. Dolph (1991) estimates that potential red fir site trees may require about 18 years to reach breast height. This translates into a site index differential between total and breast-high age base systems of roughly 30 percent.

2.3.2 Index Age

In this study, a 50-year breast-high age is used as the arbitrary standard base age definition of site index unless otherwise qualified. Site index estimates require forecasts based on statistical models. As such, they are subject to error. In general, the shorter the prediction interval, the smaller is the forecast error. Fifty years is roughly in the middle of current young growth rotation ages in the State and would tend in general to minimize forecasting errors. Thus, it appears to be a reasonable choice. In this study, the site index models developed are not tied to any particular base age. Base ages can be altered freely without changing the shape of the site curves or resulting numerical predictions.

2.3.3 Site Index Model

From a statistical standpoint, the estimation of stand site index is a double or two phase sampling procedure (Cochran, 1977). In the first (small sample) phase, a site index model is constructed. In the second phase, field samples of age and height are taken and are then used with the model to estimate site index. Both of these phases are subject to sampling error. It is common practice to ignore the sampling error associated with site model construction in estimating stand site index.

2.3.4 Stand Components and Sample Selection

In practice, rules for the selection of site trees in stands or plots are often imprecise and leave a certain degree of latitude in field procedures. One may ask 'what difference does it make?' Probably the most precise use of site index is as an independent variable in growth and yield forecasting. Experimentation with the CRYPTOS and CACTOS growth models (Wensel et al., 1987, 1986) indicates that altering site index input values by 10 percent results in differences in growth estimates of 2 – 15 percent depending on which stand attribute is being examined (basal area, cubic volume, board foot volume, stand density, age of development, species composition and a variety of other factors). As a rough rule of thumb, percentage differences in site index result in differences in growth predictions of a comparable magnitude. As further discussed in following chapters, differences in site selection rules from say, a random sample of dominant and co-dominant trees to a non-random selection of trees which are in some sense the 'best' site trees can result in differences in stand site index estimates of over 10 percent. As site index is just an index, it does not make much difference which stand component basis and tree selection rules are used. What matters in terms of making site index the most useful and precise forest measure possible is commonly accepted consistent procedures for selecting site trees. Researchers who develop growth and yield models based on different site tree definitions cause problems for practitioners who may wish to use several models in forest planning. Similarly, field procedures for site tree selection that are vague and allow a lot of subjective judgment by field personnel can be a significant source of inaccuracy in yield prediction. This topic is further explored in chapter eight with the goal of identifying site tree selection rules that are in some sense robust and stable.

2.3.5 Site Index Prediction Rules

In California, the common method of field sampling for site index is to bore trees for breast-high age and measure total heights. This constitutes the sample. The correct procedure then is to estimate site index for each sample tree and average the predictions to produce an estimate of stand site index. The sometimes-used procedure of averaging all stand sample heights and ages and making one site index prediction is to be avoided. First, all information about sampling variation (how good is the site index estimate) is lost in this procedure. Secondly, the site index curve (height versus age) must be a straight line over the age range of the sample for this procedure to be unbiased. Site curves are not straight lines. The greater the degree of curvature on site curves and age range of the sample, the more of a bias will be introduced by this method.

2.4 Stand Versus Land Classification Systems

Site index is an expression of the interaction of a particular tree population with its environment. As such, it is a stand classification system. It can only be considered a land classification system if the assumption is made that comparable populations will occupy the site in the future, the physical site evolution is stationary, climatic conditions remain comparable, and the management treatment history is constant. Management practices such as the use of genetically improved planting stock and cultural measures that increase height growth effectively raise site index in successive tree generations.

Stand site index is normally considered to be a stable stand attribute - constant for the life of a stand within the bounds of sampling variation. Cultural treatments such as logging however, can alter stand site index if tree removal prescriptions are correlated with site tree sample selection rules. In the extreme, logging may effectively remove most of the candidate site trees in a stand. As a land classification system, site index can no longer be measured. As a stand classification system, site index no longer exists.

Thus, there can be disparities in using site index as both a land and a stand classification system. No attempt is made to resolve these issues here other than to note that they exist.

2.5 Anamorphism and Polymorphism

Anamorphic site index models require only one base curve to describe the system. All other possible site index curves can be generated by a proportional or multiplicative shift of the base curve.

Polymorphism is conventionally used to describe the ability of site curve systems to express different curve shapes at different site index levels and is generally considered to be a desirable attribute of a site index model. This form of polymorphism describes differences in curve shape *between* site indices and is usually implemented by having curve shape parameters be dependent on site-specific factors. This will be denoted as Type I polymorphism.

Another form of polymorphism is associated with the possibility of having different curve shapes *within* the same site index level. In other words, there may be several stands with the same site index at one base age but differing site indices at other base ages. This essentially addresses the concerns expressed by Powers (1972a) in the introduction. This will be denoted as Type II polymorphism. Recognition of this form of polymorphism can be implemented in two general ways:

a) Develop different site index systems for each case separately. As an example, Douglas-fir site index models have been developed for coastal stands in Washington and Oregon by King (1966), east of the Cascades by Cochran (1979), and in northern Idaho and Montana by Monserud (1984).

b) Expand a base model system by introducing more explanatory variables. Monserud (1984) for example used a set of dummy (0, 1) variables to distinguish height growth patterns of Douglas-fir growing in different habitat types.

In this study, the approach has been taken to fit separate site index models for different geo-physical conditions when the situation is warranted.

2.6 Site Index Modeling Approaches

Methods employed in the construction of site index models have been extremely varied historically. These range from early anamorphic graphical studies based on single height-age pairs (e.g., Bruce 1923) to stem analysis or growth based systems with highly empirical functional forms (e.g. Alder, 1980) and models based on theoretical growth functions (e.g., Powers and Oliver, 1978; Biging and Wensel, 1985). There are however, common themes among all studies based on how the data is organized to construct site index models. At the risk of oversimplification, three historical phases of site index curve construction methods are recognized and described below. In the following and later chapters, H and A will denote a general tree height/age measurement. (H_0, A_0) will denote a specific total height and tree age and will be subsequently referred to as *initial conditions*. H_S will denote a tree total height at the site index base age A_S. H_s is traditionally called site index.

2.6.1 Guide Curve Approaches

The guide curve method dominated site curve construction techniques in the first half of the 1900's. This classical method involved obtaining a sample of single height-age pairs, constructing a single curve of height versus age by graphical or regression methods, and harmonizing this curve as the 'guide curve' to produce an anamorphic site index curve family. The base form of this model is $H=f(A)$. Site index is unknown prior to sampling and is derived by analysis. In essence, a subjective sample of total height/age pairs is drawn, the data is stratified by age, mean tree heights are computed for each age class, and the 'dots' are connected to produce the guide curve. Any growth inference that can be attributed to this method is based on an assumed equivalence of the substitution of space for time. The majority of earlier curves produced for California utilized this method (e.g., Bruce, 1923; Schumacher, 1926, 1928, 1930; Dunning, 1942). Problems with this method have been previously noted.

2.6.2 Base Age Specific Methods

Base age specific (BAS) methods of site index curve construction evolved with the general recognition that stem analysis and other forms of repeated measures on individual trees could be used to produce a more accurate assessment of dominant height growth development (Curtis, 1964). Base age specific methods minimally involve two sample points on a tree for each modeling observation. One is an arbitrary height-age measurement (H, A). The other is a height taken at the site index base age (H_S, A_S). Base age specific models are formulated in two primary ways:

Height Prediction Models: $H = f_1(H_S, A)$.

Site Prediction Models: $H_S = f_2(H, A)$.

While essentially answering different questions (Curtis et al., 1974), models produced by these two methods are commonly used interchangeably in practice. They do not give the same results even with the same data sets as a different sum of squares is minimized in each case. Similarly, altering the base age can also generate different site curve shapes even though the rest of the data remains the same (Heger, 1973). Height prediction models, which assume site index is known, are frequently used in an inverse process: find the site index that predicts the measured height at the measured age. Many height prediction models are not directly solvable for H_s and require either graphical/tabular interpolations or iterative computer solution techniques. Neither procedure can be considered statistically efficient. Finally, by using heights (or site index) on both sides of regression equations, while assuming that they do have errors when on the left hand side of the equation but are error-free when used on the right hand site of the same equation, the BAS methods violate the regression assumptions and their statistical validity. All of the stem analysis based site index curves currently used in California were constructed with base age specific methods.

2.6.3 Base Age Invariant Methods

Base age invariant (BAI) site index models in the sense of Bailey and Clutter (1974) can be considered generalizations of base age specific methods and do not require height measurements (site index) from a fixed base age in parameter estimation. Base age invariant models may have the general functional form of $H= f(H_0, A_0, A)$. In this formulation, H_0 and A_0 can be a field measurement, A can be any arbitrary site index base age and the prediction of H will give a site index estimate. Alternatively, H_0 and A_0 can be site index and site index base age respectively, A can be a desired forecast age, and H will be the predicted height at age A. Thus, base age invariant models provide a parsimonious union of both general base age specific model forms.

Base age invariant models can directly predict total height forward or backward in age given any initial conditions (H_0, A_0). Another feature is that correctly formulated base age invariant models can be used to predict future or past heights by iteratively solving the equation with small age steps or making one prediction from an initial to a terminal age. Results of either method are numerically identical.

Of more importance to this study is the feature that base age invariant models do not need an explicit tree site index (height at a base age) in order for data to be useful in constructing site index curves. Minimally, two arbitrary height/age pairs, whether from stem analysis or remeasured growth plot data, can contribute to the observation database in site index model development. BAI site index models have become popular in the south and other regions of North America (cf. Cao, 1993) but have never been used in California. Extensive experience with this method suggests that it is generally superior to base age specific methods. Further details are described in the following chapters. All of the site index models developed in this study are BAI in the sense of Bailey and Clutter (1974).

3. Base Age Invariant Site Index Models

Implementation of site index curve modeling methods involves two distinct but interrelated steps: a) development of an explicit model mathematical form, which may be implicit if a model is adapted from another study; and b) estimating the model's parameter values by fitting it to data. All site index models developed in the course of this study are base age invariant in the sense of Bailey and Clutter (1974). Details and features of the development of models of this form are described in the following chapter.

3.1 Base Age Invariant Models

While base age invariant equation forms have been in use since the 1930's (e.g., Schumacher 1939), Bailey and Clutter (1974) formalized the concept of base age invariance in site index models by proposing a base age invariant parameter estimation, through covariance analysis, which was founded on replacing a model parameter with the model initial conditions. They used what has become known as the Algebraic Difference Approach (ADA) method to derive an explicit functional site index model form that involves:

a) Identifying a suitable base equation that describes one height over age curve of the implicit form $H = f(A)$.

b) Identifying one parameter in a base equation curve that is presumed to be site specific.

c) Solving the base equation for the site specific parameter and replace all of the (H, A) terms with initial condition variables (H_0, A_0).

d) Substitute the site-specific parameter with its solution in the base equation. This will produce a base age invariant equation.

Relative to traditional base age specific equations of the form $H = f(H_s,A)$ or $H_s=f(H,A)$, a base age invariant model becomes $H = f(H_0, A_0, A)$. Thus, a three variable system has been expanded to four variables. Conceptually, rather than indexing a specific curve in a site curve family by site index (H_s), the curve is referenced by any point on it (H_0, A_0). The invariant or unchanging property of BAI models refer to predicted heights: any number of points (H_0, A_0) on a specific site curve can be used to make predictions for a specific age A and the predicted height will be always be the same. If this property is not true, then the site curves are not base age invariant.

Cieszewski and Bailey (2000) note that BAI site index models can be considered part of a more general class of models called dynamic site index equations which, in addition to the ADA, can be derived by several other methods. They proposed an extension to the ADA method called the Generalized Algebraic Difference Approach (GADA). The main addition of this approach to the ADA method is allowing more than one parameter in a base equation to be site specific.

3.2 GADA Based BAI Site Index Models

Central to Cieszewski and Bailey's (2000) method is the introduction of an unobservable site productivity or growth intensity variable (to ensure that it is not confused with the traditional concept of site index or a height at a base age) that is labeled ***X***. This variable will subsequently be referred to as the *unobserved site variable*. ***X***. ***X*** can be thought of as a function of all factors that control site and tree height growth development suitably scaled and parameterized for the modeling situation at hand. The explicit form of ***X*** does not have to be known as it is only used in intermediate steps and will eventually be replaced by a function of initial conditions and other global model parameters.

3.2.1 Development of GADA based BAI site index models

The methodology described by Cieszewski and Bailey (2000) to develop GADA based site index models can be summarized by the following five steps:

1) Select a suitable *base equation* that describes one height over age curve. With the base model parameters denoted as d_1, d_2, ... d_n, the implicit form of a base equation is

$$H = f(A, d_1, d_2, \ldots d_n)$$

2) Identify in the base equation all the parameters that potentially change for different levels of site productivity. Reformulate the base equation by replacing these parameters as functions of ***X*** and new global parameters. In GADA formulated models, all parameters are global and will consistently be denoted as b_1, b_2, ...b_n. This will produce a model of the form

$$H = f_1(\boldsymbol{X}, A, b_1, b_2, \ldots b_n)$$

3) Solve the resulting GADA formulated model in 2) for ***X***. This gives the general solution:

$$\boldsymbol{X} = f_2(H, A, b_1, b_2, \ldots b_n)$$

4) Form a specific solution for ***X*** in terms of initial conditions ($\boldsymbol{R_0}$) which is done by a one-to-one replacement of H and A in 3) with H_0 and A_0. This produces

$$\boldsymbol{R_0} = f_3(H_0, A_0, b_1, b_2, \ldots b_n)$$

5) Substitute $\boldsymbol{R_0}$ from 4) as ***X*** in 2), collect terms, simplify as much as possible, and produce the final GADA based BAI site index model with the implicit form

$$H = g(H_0, A_0, A, b_1, b_2, \ldots b_n)$$

3.2.2 A Basic Example of a GADA Formulated Model

The following example has been paraphrased from Cieszewski and Bailey (2000). Total age is used here for simplicity rather than breast-high age (breast-high age will be used in the rest of this study).

1) *Select a base model*: a basic form of Schumacher's (1939) growth function is deemed appropriate. This model describes one height over age equation.

$$H = \exp(d_1 + d_2 / A)$$

In this model, $\exp(d_1)$is an asymptote and d_2 is a shape parameter.

2) *Postulate a GADA formulated model*: The parameter d_1 is assumed to be ***X*** and the shape parameter is assumed to be directly correlated with ***X***. This gives

$$H = \exp(X + b_1 X / A)$$

3) *Solve for **X**:* Basic algebraic operations produce

$$X = \ln(H) / (1 + b_1 / A)$$

4) *Formulate R_0*: Replacing occurrences of H and A in the solution for ***X*** with the initial conditions (H_0, A_0) gives

$$R_0 = \ln(H_0) / (1 + b_1 / A_0)$$

5) *Derive the explicit GADA based BAI model form*: Substitute R_0 for ***X*** in 2), collect terms, simplify as much as possible and get

$$H = H_0 \exp\left[\frac{A_0(A + b_1)}{A(A_0 + b_1)}\right]$$

Note that the final model form in 5) does not bear a lot of resemblance to the base equation or the GADA model formulated in 2) above. This is representative of the actual GADA based models used in this study. For practitioners who wish to deal directly with manual interpolation, site index tables and graphs of all site index curves developed in this study are provided in Appendix I. For direct computations, software components compatible with Windows^{tm} are available and are described in Appendix II.

Cieszewski and Bailey (2000) also note that in the process of going through steps 2 – 5 above, superfluous and redundant parameters are often eliminated. Final explicit GADA based model forms (step 5) will never have more parameters, and sometimes will have fewer parameters, than the GADA model formulated in step 2.

Indeed, the reader may notice that even if the original assumptions on the base model parameters in 2) were expanded to say,

$$H = \exp(aX^c + bX^c / A)$$

the final GADA model in 5) would be the same one-parameter model as the one displayed earlier.

3.2.3 Features of GADA Model Formulations

While GADA based model formulations offer several advantages over traditional methods, there are restrictions on possible model forms (theories) that can be implemented with this approach. They must result in a mathematically tractable (closed form) solution for $\boldsymbol{X}$ in 3) above. Intermediate operations involve placing all terms containing $\boldsymbol{X}$ on say, the left side of the equation and all other terms on the right side. Pragmatic solution techniques for $\boldsymbol{X}$ are generally limited to the following:

a) Any equation that can be derived and reduced to a form where all left-side terms contain only one form involving $\boldsymbol{X}$ (e.g., $\boldsymbol{X}$, 1/ $\boldsymbol{X}$, ln($\boldsymbol{X}$), etc.) can be solved by basic algebraic operations.

b) Equations that result in multiple forms of $\boldsymbol{X}$ such as $\boldsymbol{X}$ and $\boldsymbol{X}^2$, $\boldsymbol{X}$ and 1/ $\boldsymbol{X}$, or suitable equivalents can be solved using the well known quadratic root solution.

c) Forms containing $\boldsymbol{X}$, $\boldsymbol{X}^2$ and $\boldsymbol{X}^3$ or forms that can be transformed into third degree polynomials can be solved using the root solution for a cubic equation.

Due to generally high redundancy in flexibility of nonlinear equations, and the possibility of isolating site dependent curve changes from mean height-age trends, the above restrictions can be overcome in various ways (Cieszewski 2001). While appearing restrictive, there is an extensive library of potential base models that are applicable to the GADA method thus allowing a wide number of GADA models to choose from to characterize empirical site tree height growth patterns. Also, as $\boldsymbol{X}$ can be arbitrarily assigned to any base model parameter(s), practical experience has shown that any fairly simple relationship of $\boldsymbol{X}$ with another global model parameter that allows a reasonable degree of freedom in the postulated direction (e.g., $b_1+b_2\boldsymbol{X}$, $b_1+b_2/\boldsymbol{X}$, $b_1/(\boldsymbol{X}+b_2)$, etc.) is normally sufficient to produce a model that is highly robust in statistical estimation. Extensive exploration to determine the best form of the relationship is usually unwarranted as they all produce virtually the same site curve shape. This is due to the definition of $\boldsymbol{X}$ being determined by trends in the data rather than requiring an explicit statement of its functional form. In contrast, base age specific methods normally require conventional site index to be explicitly parameterized. Quests for the 'best' model form can sometimes lead to over-parameterized models that extrapolate poorly at the bounds of the respective data set (c.f. Dolph, 1987).

Another aspect, which is more of a nuisance than a limitation, derives from commonly applied practices in developing site index models. Modelers developing traditional site models based on either the height or site prediction model forms may implement 'fine tuning' by directly adding terms or transforming variables in an explicit model form in efforts to better explain their data. Such modifications may be tested by refitting the model directly. With GADA based models, 'tinkering' must be carried out at the GADA model formulation level (step 2). Steps 3-5 must be repeated to implement the modifications and produce a new model form. Failure to do so runs the highly probable risk of losing the base age invariant properties of the model and ill conditioning the internal algebraic structure of the dynamic equation.

3.3 Base Age Invariant Models Used In This Study

Initially, over 12 base model forms were evaluated and anywhere from two to eight GADA based variants were developed for each. This provided a library of over 40 possible functional forms. Many seemingly different model forms and variants however, resulted in virtually the same site index curves. Thus, with a guiding philosophy of the simpler the better, only six different functional forms were used as a basis for all final site index models developed in this study.

As general notational conventions for all model development, $d_1, d_2 \ldots d_n$ are used to denote parameters in base models and $b_1, b_2, \ldots b_n$ are used for global parameters in subsequent GADA based models. All GADA based models have the general implicit form of $H = 4.5 + f(H_0, A_0, A, b_1, b_2, \ldots b_n)$. All subsequent age terms, unless explicitly noted, refer to breast-high ages.

3.3.1 Chapman – Richards Model Forms

The Chapman-Richards model form was suggested by Richards (1959) and Chapman (1961) as an extension of the growth model derived by von Bertalanffy (1957). The base model form can be represented as

$$H = 4.5 + d_1[1 - \exp(d_2 A)]^{d_3}$$

where d_1 is an asymptote or limiting value, d_2 is an age scaler, and d_3 is a shape parameter. Four of the recent stem analysis base age specific height prediction models developed for species in California have used this model form (Powers and Oliver, 1978; Wensel and Krumland, 1986; Biging, 1984; Biging and Wensel, 1985). A red fir model produced by Dolph (1991) utilized a Weibull function that is closely related to the Chapman-Richards model in form and functionality. Base age specific site prediction models developed for white fir and incense cedar by Dolph (1983, 1987) also used this model form as an integral part of the model system. Thus, this model form has a demonstrated suitability for species within the State.

CR1 Model

This model form is anamorphic (Clutter et *al.*,1983) and results from replacing the asymptote (d_1) directly with the unobserved site variable $\boldsymbol{X}$.

<u>GADA Formulation:</u> $H = 4.5 + \boldsymbol{X}[1 - \exp(b_1 A)]^{b_2}$

<u>Solution for $\boldsymbol{X}$:</u> $X = (H - 4.5)/[1 - \exp(b_1 A)]^{b_2}$

<u>Solution for $\boldsymbol{R_0}$:</u> $R_0 = (H_0 - 4.5)/[1 - \exp(b_1 A_0)]^{b_2}$

CR1 Model Form: $$H = 4.5 + (H_0 - 4.5)\left\{\frac{[1-\exp(b_1 A)]}{[1-\exp(b_1 A_0)]}\right\}^{b_2}$$

CR2 Model

This model form is a polymorphic version of the Chapman-Richards base model. Both the asymptote and the shape parameter are assumed to be dependent on ***X***. As the site variable ***X*** is arbitrary, the base equation has been re-parameterized to make a mathematically tractable solution for ***X***. The asymptote (d_1) is expressed as an exponential function of ***X*** and the shape parameter is cast as a linear inverse function of ***X***. This formulation requires a quadratic solution for ***X***.

GADA Formulation:

$$H = 4.5 + \exp(X)[1-\exp(b_1 A)]^{(b_2 + b_3/X)}$$

Solution for ***X***:

Letting

$$L = \ln(H - 4.5)$$
$$Y = \ln(1 - \exp(b_1 A))$$

Then

$$X = \frac{(L - b_2 Y) \pm \sqrt{(L - b_2 Y)^2 - 4b_3 Y}}{2}$$

Solution for $\boldsymbol{R}_0$

Letting

$$L_0 = \ln(H_0 - 4.5)$$
$$Y_0 = \ln(1 - \exp(b_1 A_0))$$

Then, taking roots most likely to be positive and real gives

$$R_0 = \frac{(L_0 - b_2 Y_0) + \sqrt{(L_0 - b_2 Y_0)^2 - 4b_3 Y_0}}{2}$$

CR2 Model Form:

$$H = 4.5 + (H_0 - 4.5)\left\{\frac{[1-\exp(b_1 A)]}{[1-\exp(b_1 A_0)]}\right\}^{(b_2 + b_3/\boldsymbol{R}_0)}$$

3.3.2 Schumacher Model Forms

Schumacher (1939) presented a growth model applicable to timber site and yield studies that, in various transformations and modifications, has seen considerable service in forest biometrics modeling efforts. In this study, the Schumacher base equation is represented as:

$$H = 4.5 + \exp(d_1 + d_2 A^{d_3})$$

where d_1 is an asymptote and d_2 and d_3 are shape parameters.

SH1 Model

This model form is anamorphic and results from replacing the asymptote (d_1) with the unobserved site variable ***X***.

<u>GADA formulation</u>: $H = 4.5 + \exp(X + b_1 A^{b_2})$

<u>Solution for ***X***:</u> $X = \ln(H - 4.5) - (b_1 A^{b_2})$

<u>Solution for $\boldsymbol{R_0}$</u>: $R_0 = \ln(H_0 - 4.5) - (b_1 A_0^{b_2})$

<u>SH1 Model Form:</u> $H = 4.5 + \exp(R_0 + b_1 A^{b_2})$

SH2 Model

This model form is polymorphic (Cieszewski and Bailey 2000) and results from replacing the asymptote (d_1) with the unobserved site variable ***X*** plus a constant and replacing the shape parameter d_2 with a linear function of ***X***.

<u>GADA formulation</u>: $H = 4.5 + \exp(b_1 + X + (b_2 + b_3 X) A^{b_4})$

<u>Solution for ***X***:</u>

$$X = \frac{(\ln(H - 4.5) - b_1 - b_2 A^{b_4})}{(1 + b_3 A^{b_4})}$$

<u>Solution for $\boldsymbol{R_0}$</u>:

$$R_0 = \frac{[\ln(H_0 - 4.5) - b_1 - b_2 A_0^{b_4}]}{(1 + b_3 A_0^{b_4})}$$

SH2 Model Form: $H = 4.5 + \exp(b_1 + R_0 + (b_2 + b_3 R_0) A^{b_2})$

3.3.3 King – Prodan Model Forms

King (1966) used a base model of the following form to express height of Douglas-fir in the Pacific Northwest as a function of breast-high age. This form was suggested by Prodan (1951).

$$H = 4.5 + \frac{A^2}{a + bA + cA^2}$$

The parameters a, b and c were subsequently expressed as functions of transformed 50-year breast-high age site index and fit to Douglas-fir data.

With a slight reparameterization to increase flexibility, a derivative of the King-Prodan base model used in this study is formulated as:

$$H = 4.5 + \frac{A^{d_1}}{d_2 + d_3 A^{d_1}}$$

Logical choices here would be to express one or both of *d2* and *d3* as functions of ***X*** for a GADA formulated model. Empirical trials indicated most variants performed similarly so only one form was used as the basis for an explicit model.

KP1 Model

This model form is polymorphic and results from replacing d_3 with the unobserved site variable ***X*** and d_2 with a linear function of ***X***.

GADA formulation: $H = 4.5 + \dfrac{A^{b_1}}{b_2 + b_3 X + X A^{b_1}}$

Solution for ***X***: $X = \dfrac{\left[\dfrac{A^{b_1}}{H - 4.5} - b_2\right]}{(b_3 + A^{b_1})}$

Solution for R_0: $$R_0 = \frac{\left[\frac{A_0^{b_1}}{H_0 - 4.5} - b_2\right]}{(b_3 + A_0^{b_1})}$$

KP1 Model Form: $$H = 4.5 + \frac{A^{b_1}}{b_2 + b_3 R_0 + R_0 A^{b_1}}$$

3.3.4 Log-logistic Model Forms

Log-logistic models, which are equivalent to Hossfeld models (Cieszewski 2003), have been used in a wide variety of population dynamic studies. Monserud (1984) applied the log-logistic model form to a site index study of inland Douglas-fir in Idaho and western Montana. Cieszewski (2000, 2001, 2002, 2003) examined several GADA formulations utilizing the log-logistic model as a base equation. A base equation for the logistic model can be represented as:

$$H = 4.5 + \frac{d_1}{1 + \exp(d_2 + d_3 \ln(A))}$$

where d_1 represents an asymptote and d_2 and d_3 are shape parameters. While several forms were investigated, one form, due to Cieszewski (2002), was found to perform particularly well in several situations.

LG1 Model

This model form is polymorphic and results from replacing d_1 with a constant plus the unobserved site variable ***X***. $\exp(d_2)$ is replaced by b_2/X. This formulation requires a quadratic solution for ***X***.

GADA formulation: $$H = 4.5 + \frac{b_1 + X}{1 + b_2/X \exp(b_3 \ln(A))}$$

Solution for ***X***:

Letting

$$L = (H - 4.5)$$
$$Y = \exp(b_3 \ln(A))$$

Then

$$X = \frac{(L - b_1) \pm \sqrt{(L - b_1)^2 + 4b_2YL}}{2}$$

<u>Solution for R_0:</u>

Letting

$$L_0 = (H_0 - 4.5)$$

$$Y_0 = \exp(b_3 \ln(A_0))$$

Then, taking roots most likely to be positive and real gives

$$R_0 = \frac{(L_0 - b_1) + \sqrt{(L_0 - b_1)^2 + 4b_2Y_0L_0}}{2}$$

<u>LG1 Model Form:</u> $H = 4.5 + \dfrac{b_1 + R_0}{1 + (b_2/R_0)\exp(b_3 \ln(A))}$

4. Data

This chapter describes the sources of data used for this study, primary tree measurements, data screening and auditing procedures, classification schema and variables, and an assessment of the accuracy of the data.

4.1 Sources

Data available for this study consist of historical stem analysis trees, repeated measurements of site tree total height on growth plots where the trees had at least one breast-high age boring, and single total height-age measurements on individual trees. In all, 17 separate data sources were utilized in one form or another. These data sources are summarized briefly as follows (source designators appear in parentheses):

4.1.1 Jackson Demonstration Forest CFI plots (JSF)

Jackson Demonstration State Forest in Mendocino County maintains 142 CFI plots located in redwood – Douglas-fir stands. Plots were measured eight times between 1959 and 1999. These data have previously been used for redwood site curves, and for the development of the CRYPTOS growth and yield model (Wensel & Krumland 1986, Wensel et al. 1987.

4.1.2 Railroad Gulch Growth Plots. (RRG)

The Railroad Gulch study contains 244 plots established on Jackson State Demonstration State Forest as part of a research project investigating growth and development of young growth redwood - Douglas-fir stands in response to different silvicultural practices and stocking levels. The plots have been measured three times on ten-year intervals between 1980 and 2000.

4.1.3 Mendocino Redwood Company Growth Plots (MRC)

These data consist of 148 growth plots located in redwood – Douglas-fir stands in western Mendocino County on property currently owned by Mendocino Redwood Company. Primary measurements used consisted of partial stem analysis (five and ten year recent height growth) on selected site trees that were felled on plot establishment.

4.1.4 Simpson Timber Company CFI plots (SMP)

These data consist of 134 clusters of 3 plots each on property owned by Simpson Timber Company. The plots were established in the mid 1960's and 1970's and have been measured continuously on a four-year cycle to the present. These plots were located primarily in the redwood/Douglas-fir forest type in Humboldt and Del Norte Counties.

4.1.5 White Fir (GspWF) and Ponderosa Pine (GspPP) Growing Space Project

As part of the cooperative Growing Space project, Drs. Edward C. Stone and Janet Cavallero have provided several hundred stem analysis measurements of dominant and co-dominant white fir and ponderosa pine trees. Approximately 350 white fir trees were available from true fir sampling sites on LaTour Demonstration State Forest, Lassen National Forest, and as far south as LaPorte. Approximately 330 ponderosa pine trees were sampled at nine major locations on the west slope of the Sierra Nevada Mountains and in the Southern Cascades.

4.1.6 Powers and Oliver Ponderosa Pine Site Index Study (POPP)

About 60 percent of the ponderosa pine stem analysis data utilized by Powers and Oliver (1978) in their ponderosa pine site index study were used in the current study.

4.1.7 Simonson Logging Growth Plots (SMN)

Approximately 20 growth plots located in redwood – Douglas-fir stands in Del Norte County on land formerly owned by Simonson Logging Co were used in this study. These plots were measured two to three times in the late 1960's and 1970's.

4.1.8 Hammond Lumber Company Growth Plots (HAM)

Approximately 20 growth plots located in redwood – Douglas-fir stands in Humboldt County on land formerly owned by Hammond Lumber Co were used in this study. These plots were measured five or six times from the early 1950's to the mid 1970's.

4.1.9 Blodgett Forest Research Station CFI plots (BFRS)

Approximately 600 growth plots located at the Blodgett Forest Research Station were made available for this study. These plots are primarily in the mixed conifer forest type. Plots have been measured four or five times in the last 25 years.

4.1.10 Northern California Forest Yield Cooperative Growth Plots (NCPlot)

Approximately 700 growth plots from the Northern California Forest Yield Cooperative were available for this study. These plots were located primarily in mixed conifer forest types in mountains surrounding the northern Sacramento valley. Plots were measured three to seven times from about 1980 to 2000. Further details are described by Wensel et.al (1986).

4.1.11 Northern California Forest Yield Coop Stem Analysis Plots (NCStem)

Stem analysis data from 39 clusters of three plots each were available from the Northern California Forest Yield Cooperative database. These plots were located primarily in coniferous forest types in mountains surrounding the northern Sacramento valley. Further details are described by Biging and Wensel (1985).

4.1.12 USFS PSW Mixed Conifer Stem Analysis Plots (LDMC)

This dataset consists of 135 clusters of two to five plots each located in mixed conifer stands on National Forest lands situated on the west slope of the Sierra Nevada Mountains. Sample locations ranged from Porterville in the south to Mount Lassen. Portions of this data were used to construct site prediction models for incense cedar and white fir (Dolph, 1983, 1987).

4.1.13 Union Growth Plots (Union)

Union Lumber Company established about 20 growth plots in the Fort Bragg area in the early 1950's in the coastal redwood - Douglas-fir forest type. These plots were remeasured three to four times between then and 1975.

4.1.14 Garden of Eden Ponderosa Pine Plots (Eden)

Dr. Robert Powers has provided 72 young even-aged ponderosa pine plots in three locations that have been subjected to various combinations of control, herbicide, fertilization and pre-commercial thinning treatments. Further details are described by Powers and Reynolds (1999).

4.1.15 USFS PSW Red Fir Stem Analysis Plots (LDRF)

As part of a Forest Service study of the growth and soil fertility of red fir forests, 56 clusters of two to five plots each were located in high elevation stands with substantial red fir components. Locations ranged throughout the Sierra Nevada Mountains and into the Southern Cascades and Klamath Mountains as far north as southern Oregon. Portions of this data were used by Dolph (1991) to construct red fir site curves.

4.1.16 Miscellaneous Redwood Cooperative Stem Analysis (RCStem)

Approximately 150 redwood and Douglas-fir tree stem analysis records from the Redwood Yield Research Cooperative archives were available for this study. Sampling locations were in redwood – Douglas-fir forest types in Del Norte, Humboldt, and Mendocino counties. Portions of this data were used for previous redwood site index models (Wensel and Krumland, 1986).

4.1.17 Forest Inventory and Analysis California Inventory Plots (FIA)

The Pacific Northwest Forest Inventory and Analysis group of the U.S. Forest Service maintains a grid of permanent sampling locations on non-Forest Service timberlands and woodlands in California. Timberland locations have five sample plots and woodland locations have three plots. Approximately 1200 timberland locations and 400 woodland locations from the 1980, 1990 and portions of the 2000 sampling cycles were used in this study. These data were used primarily in developing intra-stand species site index correlations and hardwood and minor conifer site index models.

A gross synopsis of measurements from all sources that were eventually used in some form of analysis is provided in table 4.1.

Table 4.1. Summary of numbers of stands, trees and height – age measurements by species.

Species	Stands[1]	Trees	Number of Measurements	
			Stem Analysis	Growth Plots
Conifers				
Douglas-fir	918	4299	1984	5915
Grand fir	27	94		134
Incense cedar	201	1117	1584	968

Jeffrey pine	42	488	44	494
Lodgepole pine	14	95	46	99
Ponderosa pine	852	3505	7103	4280
Red fir	110	517	3272	301
Redwood	458	3676		4932
Sugar pine	365	952	1070	1444
White fir	920	3940	11201	4555
Hardwoods				
Blue oak	59	722		722
California black oak	60	995		999
California live oak	39	443		443
California-laurel	18	239		239
Canyon live oak	60	734		734
Interior live oak	42	543		543
Oregon white oak	28	338		338
Pacific madrone	51	686		686
Red alder	18	129		148
Tanoak	149	1724		1864
TOTALS	3787[2]	25236	26304	29681

[1]Stands refer to sampling areas, plot clusters, or isolated growth plots.
[2]Stand totals reflect the number of distinct sampling locations irrespective of species.

4.2 Plot Measurements

Common plot measurements used as potential classification variables that were either measured directly or could be reasonably estimated with the aid of GIS software included the following:

1) County.

2) Data Source.

3) Stand identifier. In this study, plot clusters and specific sampling areas were considered to be in the same stand. Otherwise, plots and stands are synonymous.

4) Slope/Aspect class. Three classes were used:
   a. Flat Slope <= 15 percent
   b. NE Slope > 15 percent and azimuths of 335-360 and 0 – 90.
   c. SW Slope > 15 percent and azimuths of 90 - 335.

5) Ecological Section. Data were available from seven major Ecological Sections:
   a. Northern California Coast
   b. Northern California Coast Ranges
   c. Klamath Mountains
   d. Southern Cascades
   e. Sierra Nevada
   f. Modoc Plateau
   g. Sierra Nevada Foothills.

Subsections were also recorded.

6) Elevation Class. Classes of 500 and 1000 feet were used.

7) UTM 10 coordinates.

8) Ten-inch annual rainfall classes.

4.3 Tree Measurements

Tree measurements used in modeling and analysis consisted of the following variables:

1) Plot and stand identifier.
2) Tree identifier.
3) Total height.
4) Date of measurement.
5) Breast-high age. For stem analysis trees, breast-high ages were reconstructed from section ring counts. For growth plot trees with multiple borings, ages were determined by averaging ages over all borings adjusted for the numbers of years between borings. Otherwise, single boring ages were extended to all other height measurements by adding or subtracting calendar year differences.
6) Crown class. Crown classes used in this study consisted of dominant and co-dominant classes, upper canopy trees (either a dominant or co-dominant),and unspecified site trees.
7) Defect and damage indicators if any.
8) Species.
9) Crown ratio class. Where possible, crown ratio classes were computed based on five percent increments of the percentage of live crown to total tree height. The 20 percent class represents crown ratios of 17.5 percent to 22.5 percent, the 25 percent class represents crown ratios of 22.5 percent to 27.5 percent and so on.
10) Measurement type: stem analysis or growth record.
11) Tree site index estimate. On trees that had two sets of height and age measurements bounding 50 years, site index was estimated by linear interpolation.

4.3.1 Data Screening and Editing

All tree measurement and classification variables were uploaded into a single database and converted to common coding conventions. Most of the data sets have gone through extensive editing in the past. The data however was rechecked to insure a consistent basis for analysis. The initial data screening insured the following:

a) Trees must be classified as dominants, co-dominants, upper canopy trees, or unspecified site trees at all measurements.
b) No evidence of top damage, forked stems, excessive defoliation, or crown damage was present.

c) Trees with evidence of either rapid release or rapid slowdowns in radial increment as evidenced by ring analysis or successive DBH measurements were excluded.

Stem analysis trees were all verified to insure increasing heights with age. Growth segments that did not conform to this requirement (virtually all were apparent encoding errors) were deleted. Similarly, height/age trajectories of trees were graphically examined by stands, clusters and sampling locations to ensure all stem analysis trees were reasonable representations of the overall stand top height development. Trees that were obviously not representative were removed.

Height/age trajectories of growth plot site trees were screened in a manner similar to stem analysis trees. An added complication is that 'negative' height growth is a fact of life with repeated total height measurements on growth plots. Healthy trees with negative height growth obviously represent measurement error and the initial thought would be to delete them. One would also expect however, comparable numbers to be excessively positive due to the same types of measurement errors. These types of measurement errors are not so obvious.

A variation of the 'trimmed mean' was used to preserve the underlying data set means yet also remove obvious measurement errors. For each data source, trees were grouped into height/age classes by species. Class cell dimensions were dependent on the size of the data set. Annual height growth was then determined for each tree based on consecutive growth measurements. For each height and age class, growth series for all trees were plotted. Negative growth measurements were marked for deletion. This results in the deletion of two height/age pairs. Comparable numbers of the fastest growth measurements in each height/age class were also marked for deletion. As expected, the overall mean growth for each cell before and after trimming were virtually the same. This procedure removed about nine percent of all available height/age measurements on growth plots.

4.4 Accuracy of the Data

The data used in this study to evaluate or develop site index models is largely from stem analysis or repeated measurements of site trees. Stem analysis can be considered the most accurate method of measuring the two principal variables used in this study: breast-high age and total height. Ages determined by increment boring and total heights measured with hand-held clinometers, as is the common method of measuring standing site trees, introduces inaccuracies. Common problems with increment borings are a) missing the tree center; b) failure to reach the tree center; c) broken or compressed increment cores; d) miscounting ring numbers in the field; and e) false or missing growth rings. Sources of inaccuracies in total height measurements taken with clinometers include a) not accounting for leaning trees; b) failure to precisely locate the tree top or base; c) measuring the wrong tree; d) inaccurately measuring the ground distance; e) the native resolution of the instrument; and e) operator error in converting instrument readings to total height. Both variables are subject to encoding errors.

Approximately half of the measurements available in this study are derived from a combination of increment borings and repeated total tree heights taken with clinometers or similar devices. Inaccurate measurement of independent variables can bias regression coefficient estimates. Accuracy, or the lack thereof, is generally represented statistically as

$$\text{Accuracy} = \text{Bias}^2 + \text{Precision}$$

where precision can be taken as the measurement error variance. An ideal, replicable measurement is one where both bias and variance are zero. Both components of accuracy can contribute to bias in estimating regression coefficients if they are non-zero (Maddala, 1977).

The main concern is whether total height/age borings, which are the common practice for field site index determination, are compatible with stem analysis measurements. The following analyses were performed to check the hypothesis.

4.4.1 Total Height

The NCStem data provided 1037 stem analysis trees of all crown classes measured on 109 sample plots in 39 clusters. All trees on sample plots were initially measured for total height while standing. Stem analysis trees were subsequently felled and total heights were also determined by taping the bole length. This data set was collected by a variety of personnel from eight different private forestry firms. It can be considered a random set of measurements performed by a random selection of field personnel. This data was analyzed initially to determine if possible biases exist in measuring tree heights with a clinometer. A model of the following form was used:

$$H_c = \beta H_t$$

Where

H_c = Total tree height taken with a clinometer and chaining ground distance.

H_t = Total tree height taken by taping the tree bole after felling

β = Regression coefficient to be estimated

Results indicated that the estimate of β (.9998) was not significantly different from 1.0 ($p > .85$). This would indicate that no bias exists in this data set due to measuring total heights with a clinometer. Residuals however, were heteroscedastic with the range increasing with total height. Further analysis indicated that a constant coefficient of variation of roughly 5 percent of total tree height could reasonably characterize the error variance of measuring tree heights with a clinometer. Comparable data from 757 trees were also available from the LDMC data set. Analysis resulted in an estimate of β of .988, which was significantly different from 1.000 ($p < .001$), and a coefficient of variation of about 5.5 percent of total height. Combined, these data sets produced an estimate of β of .994, which is not considered to be practically different from 1.000.

4.4.2 Breast-High Age

Possible bias and precision of breast-high age measurements taken by increment coring were evaluated with the LDMC (726 trees) and LDRF (388 trees) data sets. Trees were bored for age while standing and subsequently felled during the same growing season. Felled trees were sectioned at breast height and rings were counted providing a stem analysis determination of breast-high age. To check for possible bias and precision in measuring breast-high ages by boring, a model of the following form was used:

$$A_b = \alpha A_t$$

Where

A_b = Breast-high age determined by increment boring.

A_t = Breast-high age determined by stem analysis.

α = Regression coefficient to be estimated.

Values of α were estimated to be .955 for the LDMC data set and .966 for the LDRF data set. Both values were significantly different from 1.000 ($p < .001$). This indicates a general underestimate of breast-high age of about four percent when borings are used. It is also noted that the LDRF data set had several trees for which the stem analysis data (ring counts and taped heights) were substituted for standing tree height and bored age measurements. Thus, the estimate of α is probably inflated. Squared residuals were linearly correlated with age up to about age 30. After this age, residual variance was homogenous with a standard deviation of about 4.4 years. Three growth plot data sets with multiple age borings on individual trees were also analyzed. Each boring could be used to estimate ages at all other measurements by adding or subtracting the years between measurements. Age variances were subsequently calculated for each tree. While an assessment of bias is not possible with this method, standard deviations based on pooled variances were found to be 2.9, 5.3, and 6.1 years for the three data sets. Combining all four sources resulted in a standard deviation of about 4.5 years.

4.4.3 Accuracy Summary

The previous analysis indicates that there are significant inaccuracies in both total height measurements taken with clinometers and ages determined by increment borings when compared with comparable stem analysis measurements. This is not to say that stem analysis measurements are necessarily error free. Also, it is unknown if the possible age bias due to increment borings noted above is restricted to the data sets analyzed or is more suggestive of problems with increment borings in general.

Statistical theory suggests that any independent variable that appears on the right-hand side of a regression equation (i.e., a site index model) that is not error free results in biased regression coefficients. Thus, we have both ages and heights (tree site index is just another height) that are prone to error. Practically, this potential problem is one of degree; it has not stopped literally hundreds of site index models from being developed in the past and put to some form of useful service. Further evaluation of these problems is contained in chapter five and in Appendix II.

5. Site Index Model Construction and Evaluation Methods

The methods that have been followed or developed in the course of this study have the goal of finding site index models that best describe the long-term height growth development of young-growth trees. 'Best' is meant to imply unbiased and of minimum variance. This was accomplished by fitting new equations and/or evaluating existing models. This chapter describes basic study parameters, site index construction and evaluation methods and the general procedures used in selecting the best site index models.

5.1 Age and Site Index Basis

Age Basis. Age in this study refers to breast-high age unless otherwise qualified. Breast-high ages are the common denominator for all available site tree data.

Base Age. A nominal 50-year base age is used to qualify references to site index. Base age invariant site index curves developed in this study do not require a specific base age. However, most previous stem analysis based models use a 50-year base age and references to the term site index need an explicit base age.

Age Range. The applicable age range of young-growth site index models examined in this study is nominally 10 to 100 years breast-high age. In order to insure good fits at the age boundaries, sample data from 5 to 120 years of age were used where possible. It is explicitly noted when age ranges depart from these standards.

Site Index. Site index will be used to reference total height in feet at a breast-high base age of fifty years. The term will be applied to site index equations, stand site index estimates, and individual tree heights at the base age.

Site Class. Site class will denote a range in 50-year breast-high age site index of 20 feet.

5.2 Species Examined

Individual species for which reasonable site index curves could be constructed or verified are:

1) Coastal redwood
2) North coastal Douglas-fir
3) Interior Douglas-fir
4) Grand fir
5) Ponderosa pine
6) Jeffrey pine
7) Lodgepole pine
8) Sugar pine
9) White fir
10) Red fir
11) Incense-cedar

12) California laurel
13) Tanoak
14) Red alder
15) Madrone
16) Black oak
17) Other oaks (California live oak, Oregon white oak, blue oak, interior live oak, canyon live oak)

Mixed conifer composite site curves were developed and evaluated for a few main geographical areas. Data were also available for several other incidental species but not in quantities sufficient to derive reasonable models.

5.3 A Pragmatic Alternative to 'Significant Difference'

Statistical detection of differences in site index curve models due to different species and geophysical conditions or assessing the accuracy of existing models may be accomplished with likelihood ratio (F-tests), student's - t, or chi square tests applied to suitable test statistics. The power of these tests is highly contingent on the sample size: the more observations, the smaller the differences that can be detected. In the course of this analysis, with sample sets frequently numbering thousands of observations, many comparisons (elevation class, slope/aspect class, ecological sections, species differences, etc.) often indicated statistically significant differences ($p < .05$) with conventional approaches. Absolute differences however, in terms of predicting heights or site index, were often minor. Visual comparisons of statistically different site index curves often did not reveal any discernible differences. Thus, it does not seem to be pragmatically useful to discriminate when empirical differences are slight even though they are statistically significant.

In order to provide a practical basis for distinguishing between possible site index models that are otherwise statistically different at conventional levels of significance ($p < .05$), three terms are introduced to denote the differences in predicted site index at age 50 when comparing models. In terms of predicting site index, models are most different in the 5-20 year age range and at 100-plus years which is the nominal upper age bound considered in this study. Differences will be less in between these age bounds and at 50 years, will not exist at all. 20 and 100 years were chosen as standard comparative ages. Differences at any age will also depend on the site index level. As standard site index reference points, data means and upper and lower 10^{th} percentile means of empirical site index distributions were chosen as reference site index levels.

1) **Negligibly different**. Differences are five feet or less. Differences in this range can result from slight alterations in sample selection and sub-sampling the same tree data set as well as different non-linear regression starting parameter estimates, convergence criteria, and solution algorithms. Models showing this degree of difference were assumed to be practically identical.

2) **Marginally different**. Differences are five to 10 feet. Site index models differing in predictions in this range that could be consistently verified were listed as sub-variants along with regional models. Choice of which site index model to use will depend on precision requirements of site index estimates.

3) **Substantially different**. Differences are over 10 feet. Differences in this range can produce site index estimates that differ by over one half of a site class (20 feet of site index). Differences of this magnitude are considered practically significant and suggest that separate site index models are warranted or abandoning one model in favor of another that is more accurate.

5.4 Site Index Construction Methods

Two main interrelated issues in estimating global parameters of base age invariant site index models involve a) how to order the available height/age pairs as dependent and independent variables and b) how to eliminate or minimize the potential bias in model parameter estimates due to imprecise or biased measurements. Detailed considerations of these items and the rationale for the methods adopted in this study are provided in Appendix II. For continuity and reference, these methods are summarized below. Other issues involve c) sample selection and choice of a suitable system of observations weights and d) minimizing the effects of periodic growth influences.

5.4.1 Observation Terms

Three terms are used below and in subsequent chapters to refer to how sample observations are ordered in model fitting or compared in post analysis. An implicit site index model expressed as a function of explanatory variables and global parameters is represented as:

$$H = 4.5 + f(H_0, A_0, A, b_1, b_2, .. b_n)$$

where (H_0, A_0) are initial conditions or site index at a base age of A_0 and A denotes a forecast age.

Forward Difference. When $A_0 < A$, younger tree ages are used to predict heights at older ages.

Backward Difference. When $A_0 > A$, older tree ages are used to predict heights at younger ages.

All Combinations. Every possible combination of height and age is used to predict all others.

Traditional height prediction site index models ($H = f(H_s, A)$) can be thought of as having backward differences for forecast ages (A) less than the base age and forward differences for ages greater than the base age. The converse is true with site prediction models ($H_s = f(H, A)$).

As shown below, these distinctions are necessary to provide a consistent interpretation of residuals in post-fitting analysis.

5.4.2 Statistical Estimation Methods

As opposed to some studies that 'average' heights and ages of all trees on growth or sample plots at specified age intervals and subsequently fit models to the composite data set, the methods employed in this study use individual trees as the primary source of observations. Two methods that are used in a non-linear regression framework were found to be the best. The first is used with repeated measurements on conifers and the last one is used exclusively with hardwoods and sparsely sampled minor conifers due to the nature of the data. The two methods are:

1) **Iterative Evaluation method** (IE). This method was adapted from an original solution technique subsequently refined by Strub and Cieszewski (2002). The intent is to remove biases in parameter estimates induced by using any form of observed heights as independent variables in regression modeling. This is accomplished by simultaneously estimating the global site index model parameters and all tree heights or site indices (the H_0 terms) that appear as explanatory variables. The procedure is iterative involving two steps per iteration. As a preliminary step, each tree has the same initial conditions assigned for all of its observations. The age can be arbitrary but, after the suggestion of Strub and Cieszewski (2002), is taken to be the average age of all ages in the trees measurement sequence (a minimum of two observations are required). The height is initially estimated to be the average height of all measurements. The procedure then proceeds as follows:

    a. The estimated initial heights of all trees are treated as constants and the global parameters in the site index model are estimated by non-linear least squares for one solution iteration.

    b. Treating the global parameter estimates from a) as constants, the initial heights of each tree are then re-estimated. This can be accomplished by running separate regressions for each tree or by separate iterative function optimizations as was used here.

    Steps a. and b. are repeated until the residual sums of squares from successive iterations stabilizes.

2) **Hardwood and Minor Conifers Method** (HMC). Hardwood and incidental conifer data comes primarily from the FIA 1980-1990 data set. All trees had a breast-high age, either from increment boring or assigned on the basis of similar size neighboring trees that had been bored. Repeated growth measurements on individual trees are unavailable because only one height measurement was taken on an individual tree during either the 1980 or 1990 measurement cycle. A smaller amount of comparable data came from scattered growth plots and isolated stem analysis data. This form of data lends itself to the classical guide curve approach, but this was not considered a viable option due to the distinct possibility of age being correlated with site index. As an alternative that has been found to perform reasonably well in practice, all dominant and co-dominant tree measurements in a stand were treated as though they constituted one tree's height/age observation sequence and the IE method was subsequently applied. At least six trees per stand with an age range of at least 20 years was a minimum requirement for stands to be considered as observation candidates. The proportions of dominant and co-dominant trees were balanced so there were approximately equal numbers at each measurement.

5.4.3 Age Difference Evaluation

As found in chapter four, available evidence suggests that breast-high ages taken with increment borings may be biased or at least 'different' from stem analysis based ages resulting from ring counts on stem cross sections. Stem analysis ages are not necessarily error-free, either. It seems highly unlikely that several decades of rings on thousands of cross sections measured by a variety of field personnel could be consistently recorded without error. Trees will seldom reach breast height exactly at the end of a growing season nor for that matter, will section cuts occur exactly at the end of a year's height growth. Age correction factors can be applied when stem analysis measurements consist of visible ring counts. Several of the stem analysis data sets have field instructions that recognize this problem and specify rounding ring counts to the closest whole year based on ring patterns at the pith. Also, several stem analysis sources specified that section cuts in the upper crowns of trees should be at growth whorls, thus eliminating the problem. In this study no attempt was made to adjust any of the stem analysis ages to account for these possible discrepancies.

In analysis however, it is a straightforward procedure to distinguish between age measurements taken by different methods. When both growth and stem analysis records were used for a specific site index analysis, the following construct Q is used in model estimation:

$$Q = (1 + d^*c)$$

Where d is a dummy variable with a value of zero for stem analysis based measurements and one for repeated growth measurements, and c is an additional global model parameter. Q was only used with the IE method. All occurrences of the forecast age in models are multiplied by Q and c is estimated along with other global model parameters. c is a nuisance parameter and is eventually discarded. If the finding made in chapter four about the difference in ages between stem analysis and age borings is widespread, we would expect the estimate of c to be of the general magnitude of about .05 for models employing different measurement types.

5.4.4 Calendar Periods

Yeh and Wensel (2000) analyzed tree basal area growth in the northern interior of California for the years 1966-1980 in relation to climatic patterns. They found significant differences in growth due to calendar periods, which they attributed to winter precipitation and summer temperature patterns. Similar analysis here of height growth over the last 100 years (1900-2000) indicated there were 'runs' in better and worse than average height growth years that sometimes extended for decades. This was mainly evident in interior mixed conifer forest types. Coastal species and high elevation true fir species did not seem to exhibit the problem to any noticeable degree.

It was decided that site index curves should nominally incorporate the average periodic influence on height growth patterns as evidenced in the 20th century (1900 – 2000). This time period is where most of the data from this study was taken. While interesting, it is irrelevant to this study what actually caused 'good' and 'bad' growth periods during the time frame; all that is needed is to know whether they happened and are evident in the data.

A problem exists in that observation ages in the site tree database are correlated with calendar years. Observations on older trees tend to come from the last few decades of the 20th century and it was suspected that weighting data sets too heavily in certain calendar ranges would unduly influence the shape of resulting site curves. Attempting to sort out possible calendar period differences is further complicated by the fact that site curves are essentially fitted as integral growth forms and periodic influences become cumulative rather than point source effects that can be associated with individual tree observations. A reasonable procedure was found however, in which periodic influences in cumulative growth forms were estimated along with all other model parameters. This procedure was routinely applied in all estimation procedures. Further details of this estimation approach are provided in Appendix II.

5.4.5 Sample Selection and Regression Weights

Site index modeling adopted here uses individual trees rather than stands (composites of individual trees) as the source of data observations. The main objective in selecting tree measurements for use as subsequent regression observations is to provide a sample that is fairly well balanced across age and site classes as well as ecological sections, topographic position classes, and elevation classes. The data however is not so well balanced. Stands (sampling locations, plot clusters, or individual growth plots) exist that, for a given species, produce anywhere from one to more than 50 sample trees. Similarly, the number of height/age measurements per tree ranges from minimally two on some growth plot trees to over 55 on some stem analysis trees. In order to equalize the relative weights of stands and trees, the following system of sample selection and regression weights was adopted:

1) No more than 10 trees of a specific species were selected from any stand.

2) If 'm' height/age observations were selected from a particular stem analysis tree, each was given a weight of 1/m.

3) Growth measurements were generally two to four times as variable as stem analysis measurements. Observations derived from growth measurements therefore were given a weight of 1/(3m), where 'm' is the number of growth measurements obtained.

Heteroscedasticity, or trends in residual variance with predicted values or other functions of explanatory variables such as (A_0 - A), did not seem to be much in evidence so further weighting additions were not implemented.

Two of the available data sets (RRG and BFRS) provide a large number of potential observations concentrated in relatively small geographical areas. Trees were systematically selected from these data sets to ensure a fairly uniform height/age coverage with the restriction that the number of trees selected was 10 percent or less of the total number of trees for the particular analysis at hand.

5.5 Procedures Used In Selecting Site Index Models

The process of selecting 'final' site index models involves numerous post-fitting analyses to ensure that chosen models are the best that can be extracted from the data.

The process is iterative rather than procedural and concentrates on accumulating evidence from as many data views and sub-analyses as possible:

5.5.1 Initial Selection of Model Forms

As noted in chapter three, over 12 base models and up to 50 variants comprised a model form database thought to represent a reasonable universe of possible site index model forms that could be applicable to species and locations in California. All model forms were not tried for every possible data set created in this project. Rather, model forms that past research has shown to be appropriate for given or like species were used as primary candidates. Also, with a large amount of data, it was possible to create empirical site curves by manually integrating growth measurements across height/age class cells. While being somewhat coarse, empirical site curves were quite useful in directing focus to specific classes of model forms.

5.5.2 Analysis of Residuals

Post analysis of residuals was initially undertaken to ensure fitted models described the data well. This analysis was to verify that there were no general trends in residuals with site index, age, and most importantly, site and age interactions. Subsequent analysis then focused on identifying trends or correlations in residuals that would indicate steeper, shallower, or somehow different site curve shaped systems could be attributed to physiographic factors or species differences.

Raw residuals from fitted models however, present a problem in post analysis. In general, if trees are growing faster than site curve predictions, they tend to have negative residuals with backward differences and positive residuals with forward differences. The converse is true for slower growing trees. While all sorts of multiple crossing and tangential patterns may be evident, this is the general pattern that has been observed. In order to provide interpretability, two main forms of residuals were analyzed:

1) Raw residuals from the fitted model. Sums of squares (or mean squares) of raw residuals are useful in discriminating between model forms fit with the same estimation method and data sets.

2) Annualized residuals. A transformed residual defined as

$$AAR = (\text{actual} - \text{predicted})/(A - A_0)$$

essentially generates positive values for tree growth series that are steeper than fitted site curves and negative values for shallower series. Annualizing the series also tends to reduce discrepancies due to comparing residuals derived from different projection lengths.

5.5.3 Post Analysis

Annualized residuals were analyzed by standard analysis of variance methods (ANOVA) using both main effects models and factorial designs so interactions could be evaluated. Factors analyzed included:

1) Source of data (data set).

2) Type of data (stem analysis or growth plot measurements).
3) Ecological section.
4) Ecological subsection.
5) Topographic position.
6) Elevation class.
7) County groups.
8) 10-inch annual rainfall class.

This form of analysis provides some indication of what factors contribute to explaining sources of residual variation and serves as basis for subdividing the observations and comparing sub-models based on factored data.

5.5.4 Variance Components

Variance components are used to indicate what proportion of the residual variation can be attributed to different factors or combinations thereof. Variance components, when expressed as a percentage of the total residual variation, indicate approximately how much of the total residual variation can be reduced by explicitly recognizing individual factors. In addition to the factors used for ANOVA, the contributions of both stands and trees were examined. When variance components are relatively large and are found to be significant in ANOVA, they serve as a focal point for further analysis and the possible development of sub-models.

Variance components are extracted by the method of expected mean squares and a variety of maximum likelihood based techniques. These methods sometimes fail due to the incomplete and unbalanced sample distribution of the data.

5.5.5 Evaluation of Models

Once a particular site index model was developed, numerous comparisons were made with competing or existing site index models deemed to be applicable to the case at hand. Both the data set used for development and independent data sets not used in model construction were used for evaluation. Residuals from predictions made with existing models were also analyzed by the post-analysis methods described above.

Variance Ratios. Comparisons of different models with empirical data were made by computing a variance statistic for each model. This statistic is defined as follows:

1. On a tree-by-tree basis, estimate the initial height (or site index) that minimizes the sums of squared residuals for the tree using the candidate model as the prediction source. This is exactly what happens in the final iteration of the IE solution method. Denoting this value as SSR_i for tree i, a mean square error is computed as

   $$MSE_i = SSR_i/(n_i-1)$$

   where n_i is the number of measurements available for tree i.

2. A pooled variance (V_k) was subsequently computed as

$V_k = \sum MSE_i/N_k$, $i = 1.....N_k$

Where k denotes model k, and N_k denotes the number of trees used with model k. Ordinarily, N_k is the same for all models but in empirical evaluations, some existing site index models 'fail' to be able to predict heights at some site index and age levels.

3. For model k, a variance ratio (VR_k) is computed as

$$VR_k = V_k/V_{bbai}$$

where V_{bbai} denotes the comparable variance from the best base age invariant model.

The variance ratio is used as a diagnostic rather than a formal test statistic. The closer it is to 1.0, the more similar models are. With suitable refinements, the variance ratio can be used as an F-statistic. With large numbers of trees (300 and above), values less than about 1.2 would indicate models are not significantly different at conventional test levels ($p <= .05$). As a rough guide, variance ratios less than about 1.1 result in negligible differences in site prediction (normally less than 5 feet). Differences in the 1.1 to 1.2 range result in marginal differences (5-10 feet).

Differences in models frequently occur in the site-age tails of empirical data distributions. In order to provide a more refined basis to evaluate models, variance ratios are computed for relative data quadrants as well as all data combined. Quadrants are delimited by the mean age of all sample trees and the mean site index of all tree measurements as predicted by what is considered to be the best overall base age invariant site index model. These quadrants are referred to as *young/low, young/high, old/low and old/high* site-age classes.

Difference Tables. Difference tables provide a practical means of judging in absolute terms what difference exists between site index models. Standard difference tables are included in evaluations of all models based on the standard age and site index ranges previously discussed in the 'pragmatic alternative' section of this chapter. The best BAI model is used as the standard basis for comparison.

5.5.6 Final Selections

Selection of a final site index model is ultimately judgmental, relying on cumulative evidence produced by various intermediate analyses, diagnostics, and data views. Choices usually become narrowed to a few models that are practically the same based on their performance with available comparative data. In these cases, fits at the 'edges' of data sets, reasonableness of extrapolation beyond the bounds of the data, and precision in the younger 10-30 year age classes are used as final criteria. In some situations, more than one final model is provided. Some very simple models have been found to perform almost as well as more complicated forms and may offer computational advantages in some applications. In other cases, one model may fit a certain age/site situation the best while another model may be best someplace else. The search for one model that fits the entire age/site range the best in all places has sometimes proved to be elusive.

5.6 Total to Breast-High Age Site Curve Conversions

Conversions of total to breast-high age site index systems has proven to be largely an academic exercise. Stem analysis records for mixed conifer site index systems (mainly Dunning, 1942) show that years from stump to breast height is correlated with site index and also varies by species. RMSE values from regressions of years from stump to breast height on site index were normally in the three to eight year range. Usually it takes five to ten years for red fir to reach an approximate one foot stump height. Thus, without knowing the exact species composition by site index, having to predict years from stump to breast height with fairly imprecise regression equations, and finally having to make educated guesses about how long it takes trees to reach stump height, makes for conversions that at best can be considered 'ball park'.

Dunning and Reineke (1933) and Dunning (1942). These total age guide curve based mixed conifer site index systems were derived from basically the same plot data sets for ages less than 100 years. Yet they have substantially different curve shapes below 100 years. Differences are mainly due to the methods Dunning (1942) employed to splice the young growth basis to the older 100-300 year old portion of his site curves. He drew a line at 4.5 feet across the total age for each set of site curves, manually interpolated the age at which this line intersected the various site curves, assumed this was years to breast height, adjusted tabled values by this amount, and fitted a base age invariant model forms to the adjusted table values. The CR1 model form fit Dunning's adjusted site curves best and the resulting model is called *MC_Dunning1942*. The CR2 model form fit Dunning and Reineke's adjusted site curves the best and the model is called *MC_DR1933*.

Powers and Oliver (1978). Powers and Oliver presented a height prediction model for ponderosa pine under stocking control for a 50-year total age site basis. Approximately 60 percent of their data (16 of 28 sampling sites) were available for this study. Site indices of trees were reclassified on a breast-high age basis and the available data was refit with the same functional form as the original equation. The breast-high age site index equation is denoted as *PP_PObha_1978*.

McArdle and Meyer (1961). McArdle and Meyers total age guide curve based site index model is for Douglas-fir in the Pacific Northwest. It forms the basis for the north coastal Douglas-fir site classification system under the CFPR. Wensel and Krumland (1986) found it did not work well based on a small sample of Douglas-fir growth measurements. These curves are re-evaluated here based on a much larger sample of north coastal Douglas-fir. Based on King's (1966) suggestion, tabled values were adjusted to breast-high ages by subtracting values of six to ten years for site classes of I to V respectively. Adjusted table values were found to fit the SH1 BAI model form the best. This model is subsequently referred to as *DF_MM_1961*.

5.7 Mixed-Conifer Site Index Models

Four existing site index models applicable to mixed conifer stands were evaluated in the course of this study: Dunning and Reineke (1933), Dunning (1942), Biging (1984) and Biging and Wensel (1985). Dunning and Reineke's curves universally performed the worst, particularly in the higher site classes. Dunning himself (1942) noted that the growth portrayed by these curves "show absurd trends towards impossible heights at older ages". Nonetheless, these curves are of historical interest and are retained in evaluation comparisons. Biging's (1984) site curves were developed primarily as an example of construction methodologies: random regression versus ordinary least squares. Unfortunately, an anamorphic Chapman-Richards type of growth form was utilized for a species group that has clearly demonstrated a high degree of polymorphism. Biging and Wensel (1985) developed a model of the same form as Biging's with the same data set by ordinary least squares with the added feature of conditioning the model so total height equals site index at a breast-high age of 50 years. This conditioning introduced a degree of polymorphism into the site curves that was in the right direction and empirically performed better than Biging's curves. Consequently, Biging's curves are not further considered. Dunning's (1942) curves also performed poorly but, as they are the basis for the generally accepted mixed conifer site class system and CFPR regulatory statutes, they were retained for subsequent evaluation and comparisons.

5.8 General Findings

In the process of preliminary analysis, several factors that could possibly influence the effects of sample selection and construction methods were examined. Several general results have emerged. These are summarized below.

5.8.1 Crown Ratios

Site trees are commonly assumed to be full crowned, well developed, and have other characteristics whose general nature is clear but lack an explicit measurable definition. As a characteristic that could be measured, the influence of crown ratio on height development of potential site trees was examined early in this study to further refine the set of possible site trees. The question is whether there should be some minimum crown ratio requirement for site trees. Dolph (1983, 1987) suggests incense cedar and white fir site trees should have crown ratios of at least 40 percent at the time of sampling. No other explicit suggestions could be found.

To examine this question, a data subset consisting of the last recorded five to ten years growth measurement sequence on all trees with recorded crown ratios at the terminal measurement were selected as a subset from data used to fit species specific site index models. This dataset amounted to approximately 5000 trees. The best initial model for each species was then used to predict growth for each tree and the residuals were subsequently expressed as annual average deviations from predicted growth. Crown ratios were rounded to the nearest five percent. A factorial analysis of variance was subsequently made with average annual deviations as the dependent variable and factors being species, crown ratio class, and 10-year age class. Species, age class and their assorted interactions were not significant. The results indicated however, that trees with crown ratios in the 10-15 percent range or less were definitely having height growth problems. Slight problems were found in the 15-20 percent range. Trees with crown ratio classes of 25 percent and greater did not exhibit any significant growth reductions.

In view of these results, trees with recorded crown ratios of less than 30 percent were not used in any subsequent analyses. Stem analysis trees only have crown ratios recorded for terminal measurements. When this value was less than 30 percent, the entire tree was discarded.

5.8.2 Crown Class

Potential site trees in this study were classified into four crown class groups: dominants, co-dominants, unspecified site trees, and unspecified upper canopy trees (either a dominant or co-dominant). This classification system was based on documentation from digitally available datasets rather than some rationally based unifying system. Most authors of site curves suggest that field site tree sample selection procedures be similar to what they used in selecting trees for their site index modeling studies. A question arises however, as to whether a single site curve system is applicable to both dominant and co-dominant trees of a particular species in a specific environment.

If it does not matter, then both dominant and co-dominant trees can be used to construct site index curves and they can all be applied to all upper canopy trees for site index prediction. Apparent differences in within stand tree heights can be attributed to within stand site index variability and age differences. This does not imply that there is no difference in site index between dominant and co-dominant trees. It only means that one site index system is capable of describing both crown classes. Site index sample tree selection procedures can be independent of crown classes used in model construction.

If it does matter, then for site index curve construction, we have to distinguish not only species but also crown class. Site index sample tree selection procedures will be dependent on crown class distributions used in model construction.

Available evidence suggests there are no significant overall differences in site curve shapes between dominant and co-dominant trees of any species. Unspecified site trees were not distinguishable from dominants. Upper canopy trees were not distinguishable from either dominants or co-dominants. As a synopsis based on approximately 12000 repeated growth measurements, residuals from the best BAI models for major conifer species (redwood, coastal Douglas-fir, ponderosa pine, sugar pine interior Douglas-fir, white fir, and red fir) were computed from forward differences for trees explicitly classified as either dominants or co-dominants. A graphical composite of mean residual by age class and crown class is shown in figure 5.1. Note that overlapping confidence bands indicate no significant difference (p=.05).

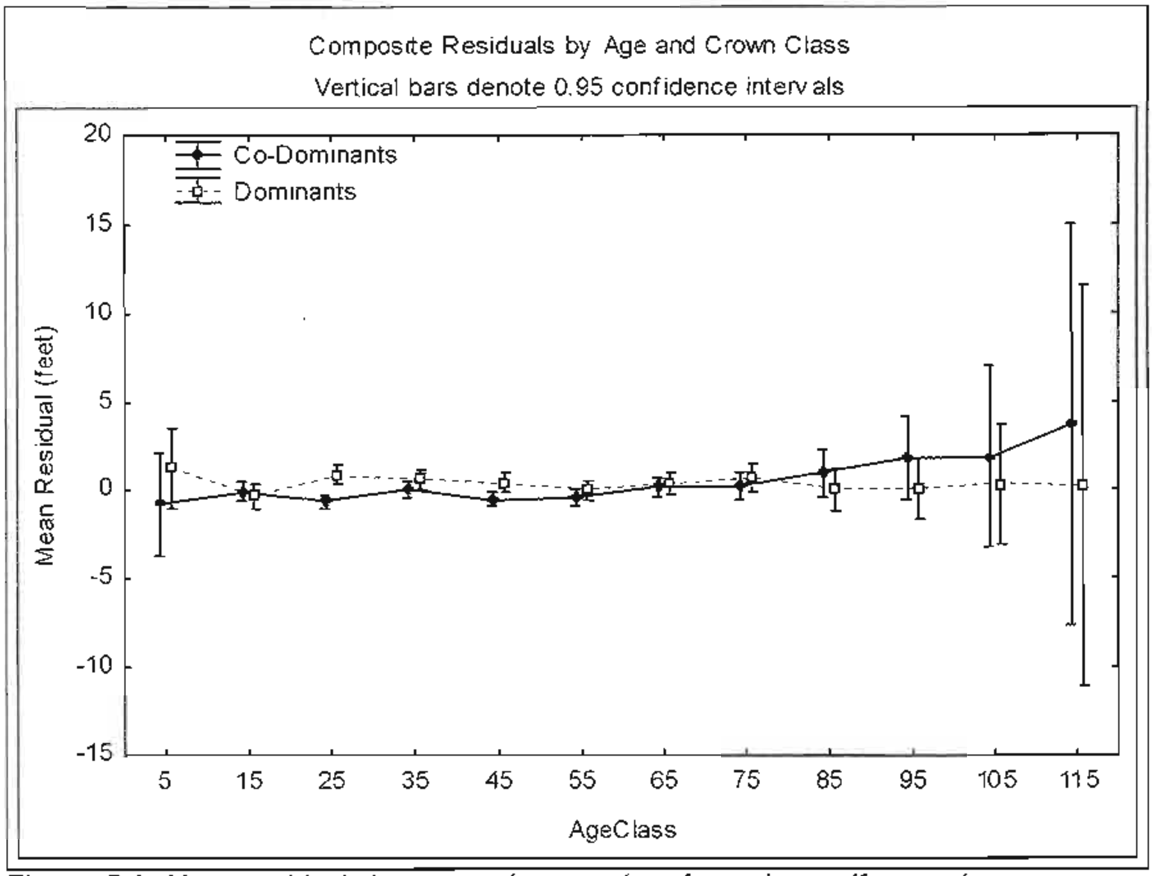

Figure 5.1. *Mean residuals by age and crown class for major conifer species.*

Suitable sample site trees from either dominant or co-dominant crown classes did not materially affect the shape of any site index curves developed in this study. Observed within-stand differences in tree heights can be attributable to within-stand site index variation and age differences. Site tree selection rules can be made independently of the sample basis used for constructing the underlying site index model.

5.8.3 Age Difference Evaluation

For all of the Northern California Coast conifers (redwood, north coastal Douglas-fir, and grand fir) for which site index models were compared or evaluated, all of the available measurements were growth plot based so discrimination between measurement types was not possible. This was also the case in situations where the HMC solution method was applied. For interior conifers where both stem analysis and repeated growth plot data on site trees were available, fitting both types of data in a single model for a specific species and location indicated consistent age difference factors in the range of -.01 to .08 for repeated measurements. Estimates less than about .01 were normally found not to be statistically different from zero. This is of the magnitude and range from the independent accuracy assessment and indicates that, across a wide variety of personnel and species, breast-high ages are probably underestimated by increment borings when compared to stem analysis measurements. In all cases examined, site curves resulting from combined measurement types with age difference corrections were almost the same (negligible prediction differences) as models based solely on stem analysis. In comparisons of pure growth plot based site curves with stem analysis based curves from comparable geographical areas, growth plot based site curves were usually steeper, particularly with polymorphic model forms. Differences between measurement types did not seem to matter much with anamorphic models.

The general approach taken where there is sufficient stem analysis data to adequately represent the age/site distribution for a particular analysis was to:

1) Use only stem analysis data to estimate the 'official' model.

2) Re-estimate the model with both stem analysis and growth plot data solely for the purpose of estimating an age difference correction term.

3) Use growth plot data adjusted for the global age difference as an independent validation set.

In situations where the age/site index distribution of stem analysis trees was inadequate to cover the range of the species, both stem analysis and growth plot data with an age difference correction were used in the estimation of specific global model parameters.

5.8.4 Calendar Periods

Deviations due to calendar periods were not evident in any of the north coastal species examined. Nor was there substantial evidence that incense cedar and red fir or white fir at elevations over 5500 feet exhibited departures from growth trends based on 'best' site index models. However, significant trends by calendar period were found through the general mixed conifer forest type for ponderosa pine, sugar pine, Douglas-fir, and white fir. Consistent patterns were noted across data sources, measurement types, species and ecological sections. A weighted species composite of estimated five-year calendar period deviations based on approximately 1800 stem analysis trees and 9000 measurements, expressed as annual percentage deviations from underlying site curve growth trends, is shown in figure 5.2.

The apparent droughts in the late 1980's and early 1990's may be a possible reason for corresponding drop-offs in height growth during these periods. What little information exists after 1997 (2000 calendar period) suggests that the depression was relatively short lived. Calendar corrections made negligible differences on resulting site curves so long as measurements were fairly well balanced across the last century. Whatever age-calendar period imbalances existed did not appear to have an appreciable impact on resulting site curves.

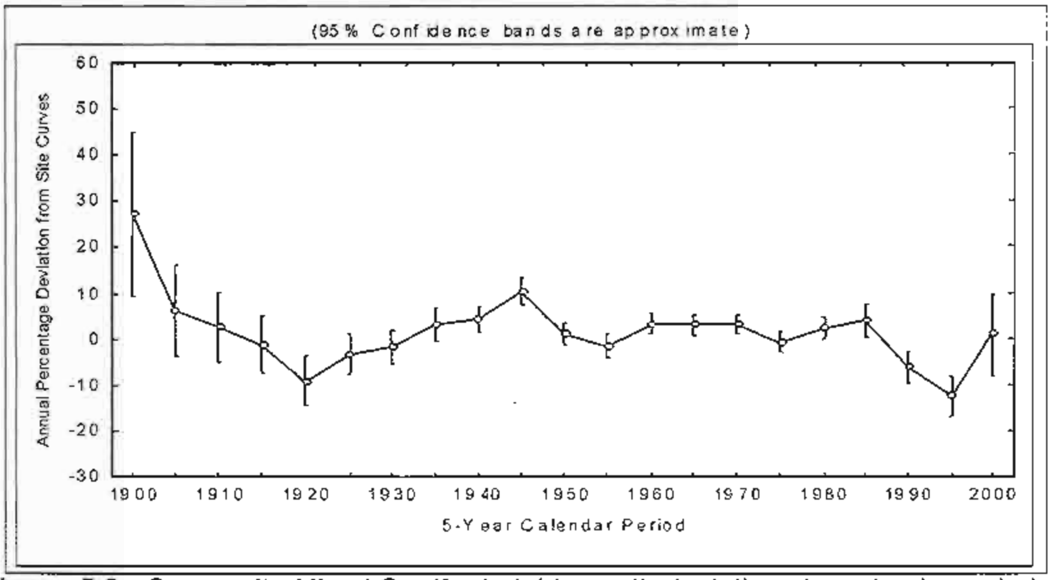

Figure 5.2. *Composite Mixed Conifer height growth deviations by calendar period.*

5.9 Sources of Variation

One of the main objectives of this study was to examine the influence of broad based physiographic factors (main effects) such as ecological section, elevation, and slope/aspect position on the shape of site index curves (Type II polymorphism). The general procedure was a) to find the best statewide BAI model for a given species or species group that was unbiased by age, site index, and age-site index interactions, b) perform an analysis of variance on annualized residuals with various cross and nested designs of the main factors, and c) extract variance components of significant factors as a percentage of the total residual variation to gain an overall measure of the magnitude of significant factors. Variance components expressed as a percentage of annualized residual variances are approximately equal to the increase in the R^2 values that would result if sub-modeling were undertaken. As an example, if a factor can account for say 10 percent of the residual variation and the general model had an R^2 of 0.95, sub-modeling could raise the R^2 to about .955. As most of the variation in height growth development is explained by site curves themselves (R^2 are normally in the range of 0.96 and greater), there is normally not much variation left that can be explained. Random coefficient site index curves (cf. Biging 1984) are also examined to place bounds on curve shapes due to Type II polymorphism.

5.9.1 Main Effects

Table 5.1 shows the percentage of residual variation by species due to main effects along with a brief description of the apparent best and worst geophysical locations associated with departures. For north coastal Douglas-fir and redwood, growth plot measurements were used as a basis as that was all that was available. For interior conifer species, results are based only on stem analysis trees.

Table 5.1. Annualized residual variance percentages due to main factors for major conifers.

Species	Ecol.[1] Section	Elev. Class	Topo. Position	Does Best	Does Worst
Redwood	4	-[2]	2	River flats	SW aspect on the eastern edge of the fog belt
Douglas-fir (Northern California Coast)	1	-	-	No apparent differences	
Ponderosa pine	5	5	1	4000 feet in elevation on flat terrain in the Sierra Nevada, Southern Cascades. McCloud flats is the stand-out	SW aspect particularly below 2500 feet of elevation. Elevations > 6000 feet
Douglas-fir (Interior)	2	3	6	Flat terrain at 3000-4000 feet elevation	SW aspect particularly below 2500 feet of elevation
Sugar pine	2	-	-	Performs the same wherever sugar pine occurs	Elevations > 6000 feet
Incense cedar	2	-	1	NE aspect	Elevations > 6000 feet
White fir	2	3	-	Does best on flat/NE aspect at elevations of 4000-6500 feet	Lower elevation mixed conifer forest types particularly SW aspect. Elevations >7500 feet
Red fir	-	1	-	Does the same wherever red fir grows	Elevations > 9000 feet

[1] Redwood and north coastal Douglas-fir use a Humboldt/Del Norte – Mendocino county division in place of ecological section.
[2] - denotes an effective variance component of zero.

Table 5.1 indicates that while often being statistically significant, the overall impact of possible main effects is relatively minor. Nor are there any apparent patterns across species. Calendar periods contribute about three percent for mixed conifers and unadjusted measure type (possible age differences) effects contribute about six to seven percent. Post adjustment, differences due to measurement types were reduced to about one to two percent overall.

5.9.2 Nested Effects

The residual variation in site curve fitting comes from somewhere. In an effort to provide a suitable partition based largely on location attributes, variance components were extracted from a hierarchical (nested) design consisting of:

ecological section → subsection → stand → tree → error

Minimally, three measurements were required per tree, three trees per stand, and three stands per ecological subsection. Only about half of the timbered ecological subsections were represented. Coastal species utilized growth plot measurements and interior species all utilized stem analysis measurements in this exercise. Results for major conifer species are shown in table 5.2.

Table 5.2. Annualized residual variance percentages for a nested design for major commercial conifers.

Species	Ecological[1] Section	Ecological Subsection	Stands	Trees
Redwood	4	-[2]	6	3
Douglas-fir (Northern California Coast)	1	1	-	-
Ponderosa pine	1	3	9	3
Douglas-fir (interior)	1	1	12	6
White fir	1	3	9	5
Red fir	-	1	12	4
Sugar pine	1	4	8	3
Incense cedar	Sierra Nevada only	3	9	4

[1] Redwood and north coastal Douglas-fir use a Humboldt/DelNorte – Mendocino county division in place of ecological section.
[2] denotes an effective variance component of zero.

The results shown in table 5.2 mainly indicate orders of magnitude as the unbalanced sample basis often required more than one estimation technique (expected mean squares, maximum likelihood, etc), which do not always produce the same estimates.

Tables 5.1 and 5.2 reveal some general patterns. First, north coastal Douglas-fir is the most 'well behaved' species. Hardly any factors or data partitions contribute much of anything to explaining residual error. One single Douglas-fir site curve applicable to the Northern California Coast would be appropriate. Indications are that there are differences between redwood site curves in the northern (Humboldt/Del Norte counties) and southern (Mendocino county) redwood units in the Northern California Coast. These will be addressed in later chapters.

For the remaining interior species, the relatively larger variance proportions due to ecological subsections when compared to sections indicates that there is more variability within sections than between them. Similarly, there is much more variation within subsections in the form of stands than between them. Within stand variation in the form of trees is generally less than half of the between stand variation or that due to type II polymorphism. Stands then are the largest contributing factor to variation in curve shape of site curve systems. Some of the main effects examined may contribute to this variability but it is evident that particular tree populations in specific locations have relatively unique patterns of top height development.

5.9.3 Random Coefficient Regression Models

A random regression coefficient analysis was undertaken for some well-represented interior conifers in an effort to put confidence limits on site index curves as they apply to individual stands. The same data subsets used in the hierarchical analysis was used for this purpose. The CR2 model form was modified so that a) the time scalar parameter (b_1) was considered to be a global species specific parameter and b) the shape parameters (b_2,b_3) were considered to be stand specific. The IE solution method was utilized to simultaneously estimate b_1, the set of stand specific parameters $\{b_{2i}, b_{3i}\}$, calendar period effects, and the remaining nuisance parameters (total height as an independent variable). Approximate 90 percent simultaneous confidence intervals were estimated for the joint distribution of the global shape parameter estimates b_2 and b_3 and used to develop bounds on site curves. As further described in the following section, an MC3 species composite (ponderosa pine, sugar pine, and interior Douglas-fir) was typical. Based on 146 stands (956 stem analysis trees), the mean and bounds for a site index 80 is shown in figure 5.3 along with all of the stem analysis data that fell into a narrow band of 78-82 feet of 'measured' site index. As can be seen, there is a reasonable compliance between site index bounds and empirical data.

These results suggest that site curves for interior conifers in California, purporting to represent broad statewide averages, will be inaccurate as a site index predictor for a specific stand. The level of imprecision is highly correlated with the difference between mean age of sampled trees and the site index base age. Results also suggest that differences in existing site curves derived by 'reasonable' statistical methods that purport to describe the same phenomena are likely to be due to sampling variation. Relatively small numbers of sampled stands are likely to exacerbate differences.

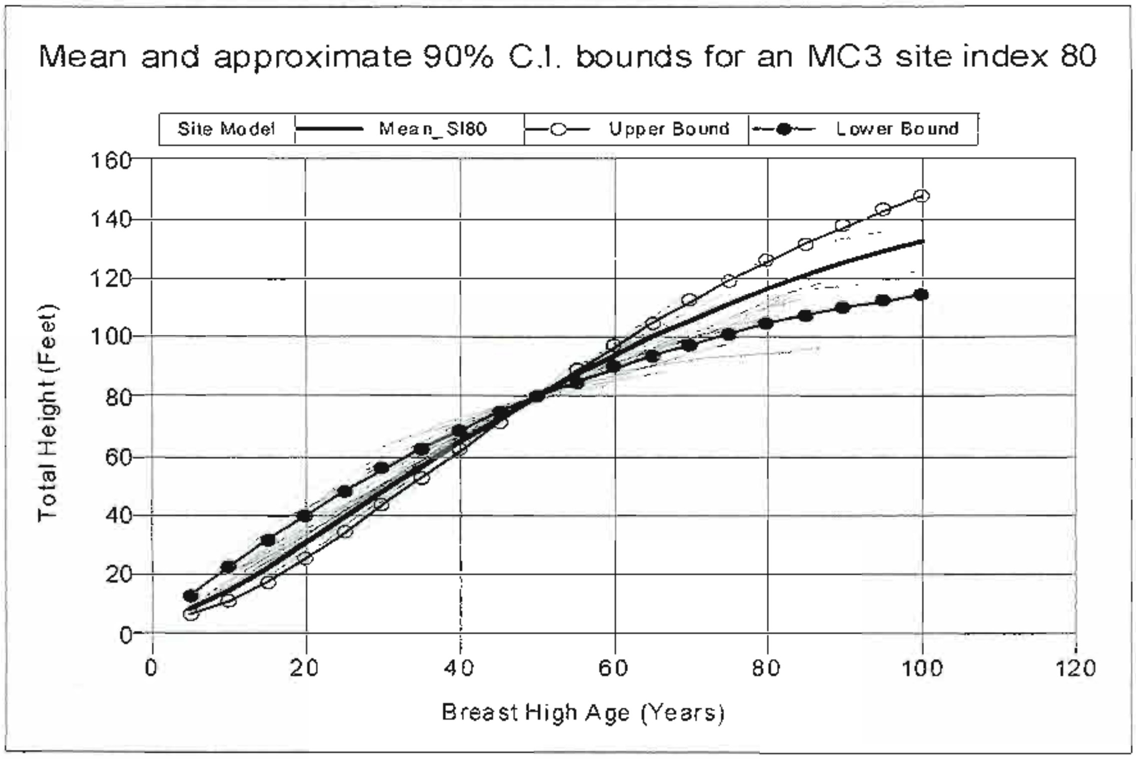

Figure 5.3. *Approximate 90 percent confidence interval bounds for an MC3 composite site index of 80 feet and representative tree data measurement sequences.*

5.9.4 Sampling Implications

Site index curves are used in general to predict the expected height at some other age given some initial height and age conditions (measurements). The prediction of site index (height at a specified base age) is just one common but special case. Given various measures of variability, what does this mean in terms of accuracy in predicting site index? Site index with heights at age 50 is used here, although any other age could just as effectively be analyzed.

To answer this question, 'best' statewide BAI site index models were constructed from stem analysis records for each of the five main interior species: ponderosa pine, sugar pine, Douglas-fir, white fir, and red fir. On a species-by-species basis, trees were selected if a) there were at least three trees per stand and b) they were at least 50 years of age at the time of felling so a 'measured' site index could be determined.

The stem analysis data used in fitting was then used to predict site index at every observation age for each tree using measured tree heights. The basic model used for analysis was

$$H50_{ij} = 4.5 + f(H_{0ij}, A_{0ij}, 50) + s_i + t_{ij}$$

Where

$H50_{ij}$	= Total tree height at age 50, from stem analysis measurements.
$f(H_{0ij}, A_{0ij}, 50)$	= The BAI model used to predict total height at age 50.
s_i	= Error due to stand i (stand effects)
t_{ij}	= Error due to tree j within stands i (tree effects)

The overall prediction error for a tree is $s_i + t_{ij}$. The s_i term represents between stand variability or departures from $f(H_{0ij}, A_{0ij}, 50)$. The t_{ij} term represents within stand variability or individual tree departures from s_i. Put another way, the t_{ij} represent departures from mean stand predictions and the s_i represent departures of mean stand predictions from the average stand site index. These terms are assumed to be independent which seems reasonable. For each species (model), variances of the s_i and t_{ij} terms plus totals ($s_i + t_{ij}$) were computed based on a10-year age stratification. All species showed the same trends and same general magnitudes. Consequently, data from all species were combined (228 stands, 1644 trees, and 12703 measurements) and pooled variance components were computed. RMSE values (standard deviations) for each component are shown in figure 5.4.

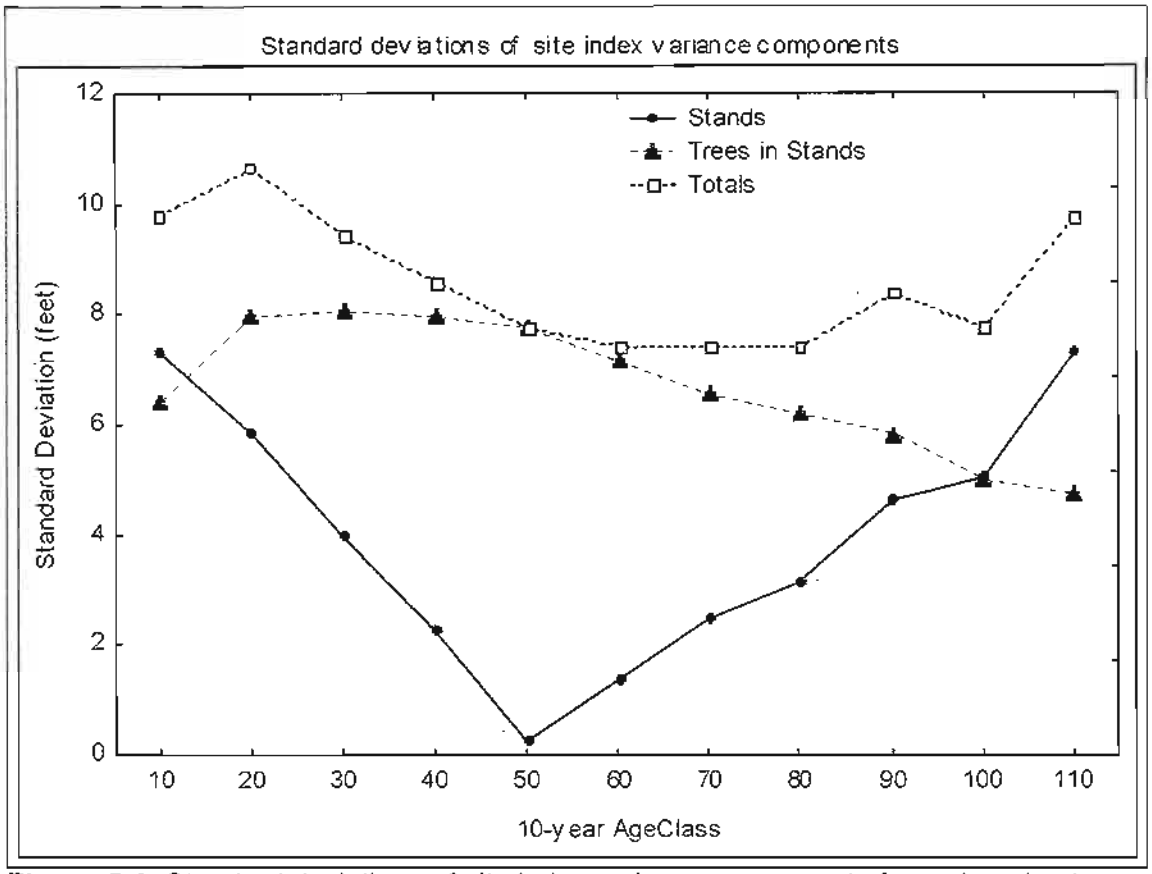

Figure 5.4. *Standard deviations of site index variance components for major mixed conifers.*

Stand Effects. Values for the stand effects (departures from site curves) are highly consistent with the confidence limit bounds determined by the random coefficient analysis. Two different ways of examining site curve variation due to stands indicate the same general magnitude. This source of variation is a constant in field site index determination and can only be reduced by a) developing site index curves that are more site specific; b) selecting trees that are closer to a desired base age; or c) extending the conventional site index determination procedures from one height/age point to two or more to account for type II polymorphism.

Tree Effects. Tree effects here represent the within stand site index variability among trees plus temporal and measurement error effects. Note that this source of variation is fairly constant across age classes, decreasing slightly in older age classes. In estimating this value, all of the qualifying site trees in stands were pooled regardless of crown class. This source of variation in estimating stand site index can be controlled by:

1) Sample size. The more site trees sampled, the lower will be the standard error of the estimate.

2) Adopting stand component selection schemes (rules for selecting dominants and co-dominants) that minimize the within stand site index variability.

3) Measuring trees more precisely to minimize total height and age measurement errors.

Krumland and Wensel (1977) found that comparable tree RMSE values were 11.3 feet for stand ages less than twenty years and 8.3 feet for stands over 20 years of age. These values are larger than those shown in figure 5.4. The difference is probably because they were based on field determination of heights and ages rather than stem analysis as used here. King (1966) performed a comparable stem analysis based study for Douglas-fir and determined a value of about 6 feet for trees over 35 years of age. His choice of site trees in plots however, was based on clearly defined and repeated sampling rules. This aspect is further explored in chapter eight.

5.9.5 Sources of Variation Summary and Discussion

Differences of the magnitude shown by both the random coefficient analysis and sampling analysis indicate that statewide site index curves for interior conifers have bounds of at least one full site class (20 feet) for individual stands evaluated at about 20 and 100 years of age. These differences however, diminish proportionately as stand ages approach the index age. Thus, while statewide site index curves may be unbiased overall, application of the curves to estimate site index for any specific stand not close to the site index base age (at say, 20 years of age) will be relatively imprecise and probably biased. No amount of individual site tree samples within a stand can reduce the influence of type II polymorphism. Several main effects have been identified as possible sources that may be incorporated in site index model systems to reduce between stand variability. The overall impacts however, result in shades of gray rather than a clear-cut basis to discriminate between possible site curve forms. Attempting to incorporate all effects in a systematic fashion also goes far beyond the limits of available data. Having to be armed with a portable GPS and a dichotomous key to determine the most appropriate site index curves for a particular location does not seem to be a pragmatic solution to the problem either.

The approach adopted was to stratify the data into a few major strata that clearly resulted in reductions in site curve variability and could be implemented in a straightforward manner.

6. Site Index Model Analysis and Results

This chapter provides a description and synopsis of analyses made in constructing new base age invariant site index models and evaluating existing ones. Sample distribution maps and site index model graphs and tables for most models developed in the course of this study are provided in Appendix I.

In the following chapters, descriptions of the range of individual species have been extracted from Griffen and Critchfield (1972). Accounts of abundance and stocking are based on the 1980 – 1990 USDA Forest Service Forest Inventory and Analysis California forest inventory.

6.1 Site Index Model Naming Conventions

As several different site index models were developed, conventions were established so they could be referred to by concise and meaningful names. Names for site index models have the general form:

SP_Model_Location

where *SP* is the species code from table 1.2, *Model* is one of the explicit base age invariant model forms presented in chapter 3, and *Location* is an abbreviation to designate a specific set of geo-physical factors. For example, the red fir model fit to the CR2 model form for all available data in California is called *RF_CR2_Ca*.

Existing site index models are generally identified as:

SP_Author_ Date

where *SP* is the species code, *Author* is the model developer(s) – entire last name if a single author or first initials of last names for multiple authors - and *Date* is the year of publication. For example, the mixed conifer model developed by Biging and Wensel (1985) is denoted as *MC_BW_1985*. The white fir model developed by Dolph (1983) is denoted as *WF_Dolph_1983.*

6.2 Major Geophysical and Species Strata

This study investigated the influence of physiographic factors such as ecological section, elevation, and slope/aspect position on the shape of site index curves (Type II polymorphism). Several factors were identified as possible sources that may be incorporated in site index model systems to reduce between stand variability (see section 5.9). The overall impacts however, do not provide a consistent basis for choosing between different site curve forms. Attempting to incorporate all effects in a systematic fashion also goes far beyond the limits of available data. The approach adopted in this study was to stratify the data into a few major strata that clearly resulted in reductions in site curve variability and could be implemented in a straightforward manner.

6.2.1 Douglas-fir

Douglas-fir is the most abundant commercial forest species in California in terms of volume and basal area stocking. It ranges from the coastal redwood/Douglas-fir forest type through the Northern California Coast, Klamath Mountains and the Southern Cascades ecological sections, and is a major component of the Sierra Nevada mixed conifer forest type. It seldom occurs east of the Sierra Nevada – southern Cascades crest.

Douglas-fir site index usage has traditionally made a distinction between north coastal Douglas-fir and Douglas-fir sites in the interior. Data available to this study indicates the majority of north coastal Douglas-fir site indices range from about 90 to 175 feet while in the interior the range is about 40 to 120 feet. Thus, the lower end in the Northern California Coast corresponds to the higher end in the interior. Attempting to find one Douglas-fir site curve system applicable to the entire State is probably heroic and the historical distinction is probably justified. Thus, separate site index models are developed for Douglas-fir based on a Northern California Coast and 'rest of the State' stratification. The species code DF will be used to denote Douglas-fir in the Northern California Coast and DFI will be used for the interior.

6.2.2 Major Mixed Conifers

There are six major interior mixed conifer species (ponderosa pine, sugar pine, Douglas-fir, white fir, red fir and incense cedar) that have sufficient amounts of data and geographical sampling distributions to allow species specific analysis. Based on the data used in this study, it was not possible to distinguish between ponderosa pine, sugar pine, and interior Douglas-fir regardless of where they grow. This group will be collectively designated as *MC3*. Red fir and white fir are notably different from this group as well as each other. Incense cedar is in a class by itself. Three different geographic strata were created for the major mixed conifers species group.

1) Main Mixed Conifer Zone. This term will denote mainstream mixed conifer forest types on the west slopes of the Sierra Nevada and the southern Cascades, generally west of the crest, that are clearly not east side pine types. A main criterion is that the sites can support associations of sugar pine, ponderosa pine, Douglas-fir, and white fir. Elevations should be between 2500 and 6000 feet and sites should not include areas where ponderosa pine, sugar pine, or Douglas-fir appear as minor incidentals in what are apparently true fir sites. Also included in this zone are mixed conifer types in the Klamath Mountains that show definite mixtures of ponderosa pine, sugar pine, interior Douglas-fir, and possibly white fir. These stands largely occur in the 3500-5500 feet elevation zone. Areas surrounding the McCloud flats are excluded and treated as a separate case. This general area is the main mixed conifer belt in California and comprises over 80 percent of available MC3 data. The other mixed conifer area delineates further the areas not included here.

2) Other Mixed Conifer Zone. This term will denote locations that can be considered mixed conifer fringe areas or east side pine types. Areas included are:

a) All of the Modoc Plateau.
b) All east side pine types.

c) All of the Northern California Coast Ranges ecological section. Four separate data sources all indicate a general relative flattening of site curves beyond 50-60 years of age of all MC3 species in this ecological section.
d) All predominantly interior Douglas-fir forest types in the Klamath Mountains ecological section. These stands largely occur below elevations of 3500 feet.
e) Sites that have true oaks (other than black oak), California foothill pine, or any form of interior juniper as associates.
f) Areas with 20 inches or less of annual precipitation.
g) All true fir sites where MC3 species appear as minor associates.
h) All low elevation ponderosa pine sites that occur in the transition zone between oak woodlands and mixed conifer forest types. This zone ranges from about one to twenty-plus miles in width and occurs all along the eastern side of the Sacramento Valley. While incense cedar may be an associate, the general feature is a general lack of sugar pine, Douglas-fir, or white fir.

3) McCloud Area Zone. Four separate data sources (NCPlot, NCStem, POPP, GspPP) provide data from an area consisting of the McCloud Flats ecological subsection (M261Dg), the southeastern portion of the High Cascades subsection (M261Df), and the extreme northern portion of the Hat Creek Rim subsection (M261Dj) largely north of Lake Britton. Soils in these areas are largely derived from alluvium, volcanic ash, and other glacial debris from the eastern side of Mt. Shasta. Data from this area distinguishes itself by indicating that height growth does not slow down in the 60 – 100 year age range relative to other zones. This is a relatively small area and location specific site curves will not have much general utility except for local landowners. Site curves based on data from this area are primarily used as an indicator of the range in variability of type II polymorphism that exists in the resource. This area, despite its reputation as a highly productive site, does not contain the highest site indices observed in the data.

This mixed conifer zone classification reduced variation in MC3 species site curve development by about 40 percent.

6.3 Conifer Site Index Models

In this section, a data synopsis and statistical summary is provided for each BAI model developed for different conifer species. Comparisons with existing site index models are also provided. In the statistical summary tables, coefficient estimates, R^2 value, and an RMSE (weighted standard deviation of residuals about the site index model) value are supplied.

6.3.1 Redwood

The major commercial range of redwood spans the Central and Northern California Coast ecological sections. In the Northern California Coast, there are two major concentrations of redwood: Humboldt-Del Norte county and Mendocino-Sonoma county with a discontinuity in the range of redwood appearing at roughly the Humboldt-Mendocino county border. In the Central California Coast, major concentrations of redwood are in the Santa Cruz Mountains and southern San Mateo County. In this study, no data is available from the Central California Coast or Sonoma County.

Past redwood site studies consist of those by Bruce (1923), Lindquist and Palley (1961), and Wensel and Krumland (1986). Bruce's guide curves were for trees less than 60 years of age and are seldom used. Curves produced by Lindquist and Palley and Wensel and Krumland (*RW_WK1986*) are similar at breast-high ages over 30 years and site indices greater than 80 feet. Wensel and Krumland found that Lindquist and Palley's curves overestimated site index in ages less than 30 years and for low site indices. The largely independent data set used in this study confirms these earlier findings.

The initial analysis was based on redwood data from the entire Northern California Coast. All the available data were growth plots with trees predominantly of sprout origin. A summary is shown in table 6.1. About eight percent of the trees used in this study were also used by Wensel and Krumland for their previous study. Otherwise, this study provides an independent and much larger sample basis for a redwood site index analysis. The polymorphic KP1 model form provided the most consistent and precise fit of all models tested. This was followed closely by the anamorphic CR1 model form with a loss of precision of about two percent.

Table 6.1. Redwood site index data summary.

Variable	Sample Statistics			Sample Size	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft)	92	34	29 - 175	Stands	225
Age (years)	43	21	9 - 96	Trees	645
Site Index (ft.)	106	19	68 - 142	Observations	1459

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Analysis of residuals indicated the only significant partition of the data that could be made was based on counties: the northern unit consisting of Humboldt and Del Norte counties and the southern unit consisting of Mendocino County. Redwood site index curves tended to be slightly steeper for a given site index in the northern unit. However, the age/site index sample distributions were not uniform by unit. The northern unit averaged about eight feet higher in site index with an age range of five to 70 years. The age range in the southern unit was about 30-110 years. Separate models did not extrapolate well outside their age ranges. Thus, while there may be differences between the units, the sample basis was insufficient to discriminate at this time. Consequently, two redwood site index models (*RW_KP1_NC, RW_CR1_NC*), applicable to the entire Northern California Coast, were considered to be the best that could reasonably be extracted from the data. The KP1 model is considered to be the best but the CR1 model is not much different and, due to its simple form, can be directly embedded in electronic spreadsheets. Parameter estimates are given in Table 6.2.

Table 6.2. Statistical summary for the RW_KP1_NC and RW_CR1_NC redwood site index models.

Model Name	Model Form	Parameter Estimates			RMSE (ft.)	R^2
		b_1	b_2	b_3		
RW_KP1_NC	KP1	1.089	-0.2131	203.4	9.90	.998
RW_CR1_NC	CR1	-0.0161	1.096	--	9.91	.998

Redwood Evaluation and Comparisons

The two site curves developed here and those of Wensel and Krumland (1986) are shown in Figure 6.1 for comparative purposes. The *RW_WK1986* model allows for a high degree of polymorphism. However comparisons with the anamorphic and polymorphic models developed here suggest that whatever polymorphism exists is minor. The Wensel-Krumland curves were also for trees up to 80 years of age while the entire Northern California Coast sample in this study included trees up to 110 years of age.

Using the *RW_KP1_NC* model as the basis, variance ratios are shown in Table 6.3 and differences in predictions are shown in Table 6.4. By all criteria, differences between these curves at worst can be considered negligible. The most visually apparent differences occur on high sites at advanced ages. However, there were virtually no observations available for this data range and apparent differences represent extrapolations. Overall, site index predictions made by these three models differ less than about five feet for site indices in the 80-140 range and ages less than 80 years. This range represents over 90 percent of the sample basis used in this analysis.

Table 6.3. Variance ratios for redwood models using RW_KP1_NC as a basis.

Model	Age-Site Class				
	Young/Low	Young/High	Old/Low	Old/High	Overall
RW_KP1_NC	1.00	1.00	1.00	1.00	1.00
RW_CR1_NC	1.01	0.99	1.00	1.06	1.02
RW_WK_1986	1.08	.99	1.12	1.02	1.04
Trees (Obs.)	157(337)	125(267)	163(355)	145(322)	654(1459)

Table 6.4. Difference in site index predictions (feet) from RW_KP1_NC model by classification age and site index class.

Model	20 Years BHA			100 Years BHA		
	Site Index Class			Site Index Class		
	Low	Ave.	High	Low	Ave.	High
RW_WK_1986	5	5	6	0	3	5
RW_CR1_NC	1	0	4	3	3	1

Redwood Summary and Recommendations

There is little to suggest that the model of Wensel and Krumland (1986) or the *RW_KP1_NC* and *RW_CR1_NC* models developed here differ appreciably. Based on our pragmatic criteria, they are all the same. The *RW_KP1_NC* model gives slightly better estimates in the younger ages (less than 20 years) than any of the other models when compared with the data used in this study. The *RW_CR1_NC* model uses two rather than the nine parameters of the *RW_WK1986* model and is thus much simpler. Both of the models developed here have the desirable base age invariant characteristics of direct and compatible site index and height predictions making them much more amenable to electronic data processing.

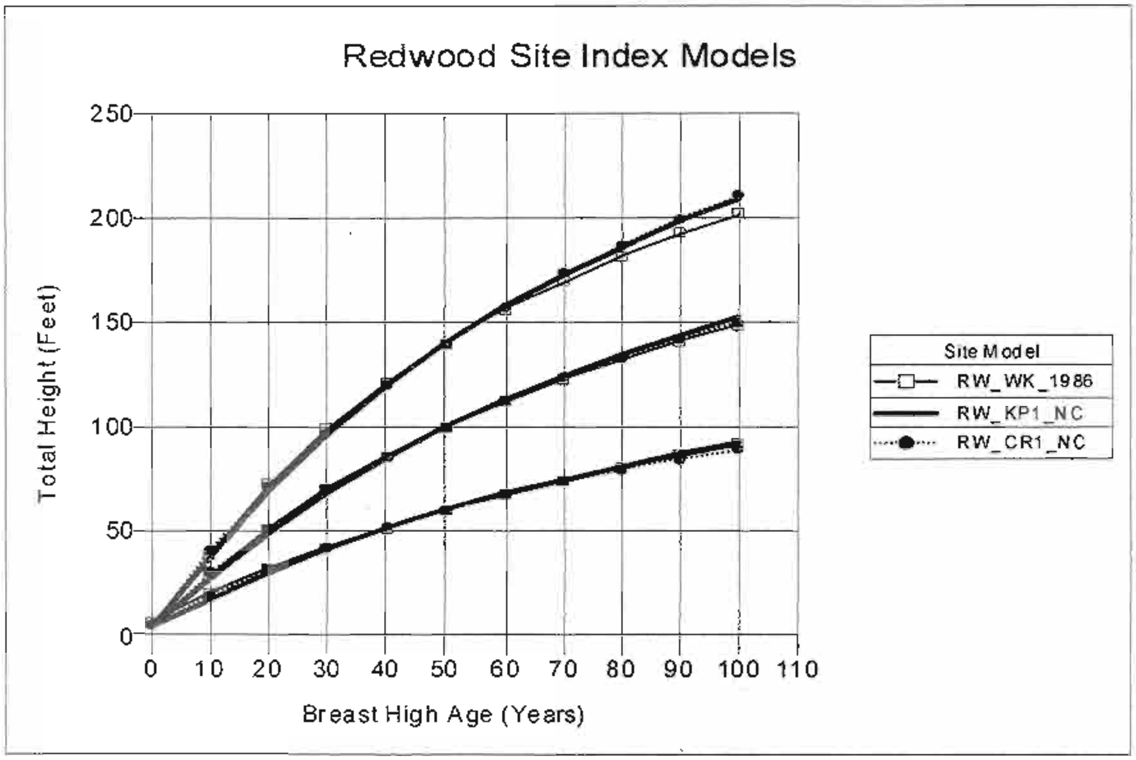

Figure 6.1. *Redwood Site Index Curves.*

6.3.2 North Coastal Douglas-fir

Past site index studies of north coastal Douglas-fir in California have been limited to Schumacher's (1930) statewide species-specific work. Wensel and Krumland (1986) compared several Douglas-fir site curves potentially applicable to the Northern California Coast with periodic height growth measurements taken from permanent growth plots in the redwood region. In general, curves by Schumacher (1930) and McArdle and Meyer (1961) for the Pacific Northwest were found to be similar but biased. King's (1966) curves, developed for coastal Douglas-fir in Oregon and Washington, appeared to be the best fit for north coastal Douglas-fir in California. King (1966) and Curtis (1966) also found similar problems with McArdle and Meyer's curves for Douglas-fir in the Pacific Northwest. King's curves are used by several organizations in the redwood region and are informally considered to be the best 50-year breast-high age base site curves available for north coastal Douglas-fir.

In this study, data available for north coastal Douglas-fir sites was largely coincident with the north coastal redwood/Douglas-fir forest type in Humboldt, Del Norte, and Mendocino Counties at elevations of about 2500 feet or less. Approximately 15 percent of the available tree measurements were from the eastern side of the Northern California Coast ecological section where redwood was not in evidence. No data from the Central Coast or Sonoma County were available.

The initial analysis was based on Douglas-fir data from the entire Northern California Coast. The available data was all growth plot based and a summary is shown in table 6.5. The polymorphic King-Prodan model (KP1) produced the best and most consistent fit of all the models tested and was named *DF_KP1_NC*. The totally different CR2 model form produced almost the same site curve family and was taken as a confirmation that the site curves produced by the KP1 model form were not being constrained by model functionality. Interestingly, the SH1 model form produced site curves that were almost coincident with King's model. The model was named *DF_SH1_NC*.

Parameter estimates and a statistical summary for the *DF_KP1_NC* and *DF_SH1_NC* models are shown in Table 6.6. Analysis of residuals indicated similar differences as those found with redwood between the northern and southern redwood units were apparent but to a lesser degree. Similar age class range differences prevented any more detailed analysis.

Table 6.5. North coastal Douglas-fir site index data summary.

Variable	Sample Statistics			Sample Size	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height (ft)	91	35	31 - 185	Stands	194
Age (years)	34	16	12 - 79	Trees	545
Site Index (ft.)	122	20	78 - 164	Observations	1204

[1]Range is based on the means of the lowest and highest 10^{th} percentile of the distribution

Table 6.6. Statistical summary for north coastal Douglas-fir site index models.

Model Name	Model Form	Parameter Estimates			RMSE (ft.)	R^2
		b_1	b_2	b_3		
DF_KP1_NC	KP1	1.221	-0.8755	402.8	6.10	.998
DF_SH1_NC	SH1	-9.033	-0.4802	–	6.45	.994

North Coastal Douglas-fir Evaluation and Comparisons

The two site curves developed here, those of King (*DF_King_1966*) and the site curves of McArdle and Meyer (*DF_MM_1961)* converted to a breast-high age basis are shown in Figure 6.2 for comparative purposes. Variance ratios for the data described in table 6.6 using the *DF_KP1_NC* model as a basis are shown in table 6.7. Site prediction differences are shown in table 6.8.

Table 6.7 Variance ratios for north coastal Douglas-fir site index models using the DF_CR2_NC model as a basis.

Model	Age-Site Class				
	Young/Low	Young/High	Old/Low	Old/High	Over All
DF_KP1_NC	1.00	1.00	1.00	1.00	1.00
DF_SH1_NC	1.16	1.00	1.02	1.01	1.08
DF_King1966	1.13	0.99	1.00	1.01	1.05
DF_MM_1961	1.29	1.21	1.15	1.04	1.26
Trees (Obs.)	172(389)	54(108)	163(355)	83(172)	545(1204)

Table 6.8. Difference in north coastal Douglas-fir site index predictions (feet) from the DF_CR2_NC model by model, classification age and site index class.

Model	20 Years BHA			100 Years BHA		
	Site Index Class			Site Index Class		
	Low	Ave.	High	Low	Ave.	High
DF_SH1_NC	-6	-2	7	5	1	-7
DF_King1966	-5	-2	5	7	3	-6
DF_MM_1961	-13	-12	-8	13	11	6

McArdle and Meyer's model performed the worst, underpredicting site index at ages less than the base age and overpredicting at older ages. The findings here are consistent with past observations by King (1966) and Wensel and Krumland (1986).

The *DF_SH1_NC* model is almost coincident with King's at ages over 15 years. For younger ages, it is lower than King's model. This will result in an overprediction of site index and it should not be used in this age range.

Visual inspection and the diagnostic tables indicate there is not much difference between the DF_KP1_NC models and King's (1966) older curves. Particularly in the main site index range of about 110 – 150, the curves are almost the same at ages about 70 years and less. Figure 6.2 shows that visual differences appear at older ages on high sites. This is outside the basic age/site range used in this study. King also had very little data from this area so both curves are essentially extrapolations and differences should not be considered significant. On lower sites (< 80 feet), differences between these two models are more pronounced with King's curve being flatter. Data from lower sites came primarily from the eastern edge of the Northern California Coast ecological section and western slopes of the Northern California Coast Ranges, effectively outside of the redwood/Douglas-fir forest type. Comparative analysis indicates that for sites less than 100 feet, the *DF_KP1_NC* model form is almost coincident with interior Douglas-fir models based on the CR2 model form, all stem analysis data, and main sampling areas being the eastern sides of the Klamath Mountains and Northern California Coast Ranges ecological sections. Suspected differences in site curve shapes between interior and north coastal Douglas-fir may not be as significant as previously expected.

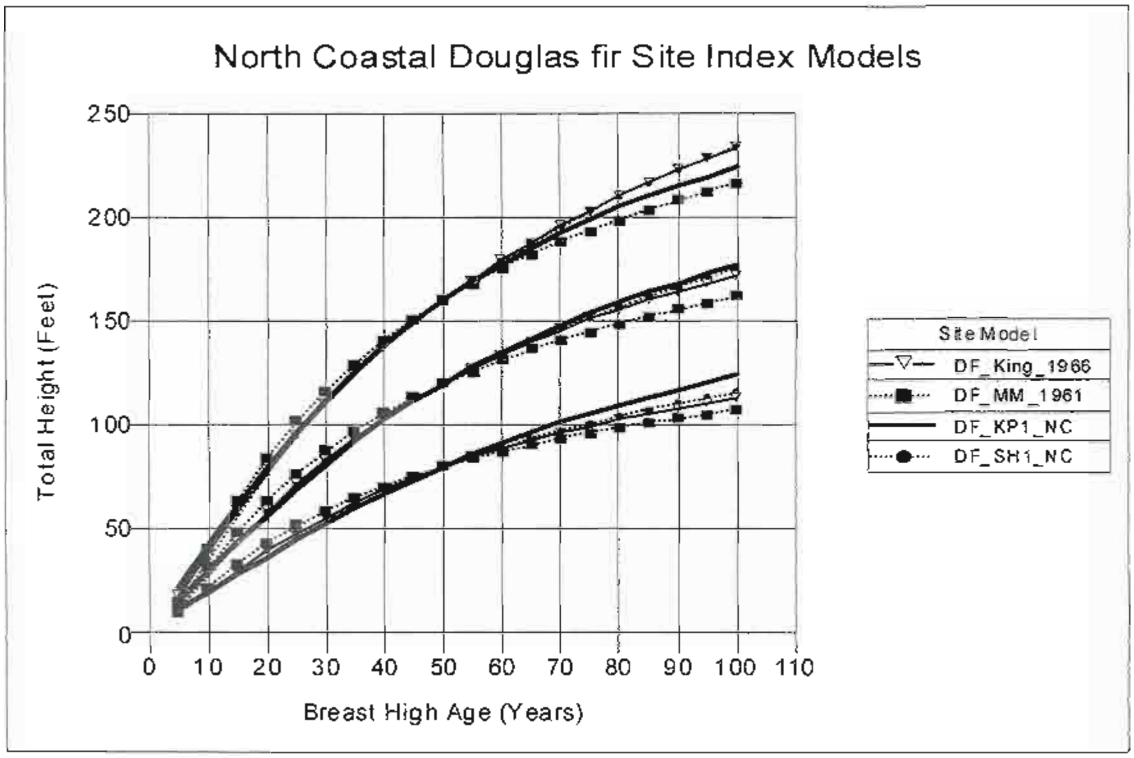

Figure 6.2. *North coastal Douglas-fir site index models.*

North Coastal Douglas-fir Summary and Recommendations

The *DF_KP1_NC* model was found to be the best fit of the data available to this study and is the recommended Northern California Coast Douglas-fir site index model. In the redwood/Douglas-fir forest type on better sites, differences between this model and King's are minor and the two can be considered practically the same. The less precise *DF_SH1_NC* model almost replicates King's curve at ages over 15 years and can be directly embedded directly in simple equation form in spreadsheet and related software if a replacement for King's model is desired. The *DF_KP1_NC* model has desirable base age invariant properties and is recommended. Older curves of Schumacher (1930) and McArdle and Meyer (1961) should be avoided where possible.

6.3.3 Grand Fir

Grand fir is largely limited to the Northern California Coast ecological section in California at elevations below 2000 feet. It occurs mainly as an associate in redwood - Douglas-fir stands. No site index studies have been made specifically for grand fir in California. Both Schumacher (1930) and Wensel and Krumland (1986) have noted that total heights of grand fir growing in mixture with even-aged Douglas-fir are quite similar and concluded that Douglas-fir site index curves could be used for grand fir.

The sample size of grand fir available for this study is relatively small and spans a narrow site index and age band (Table 6.9). Initial analysis confirmed that heights of grand fir are comparable to Douglas-fir in apparent even-aged stands in the age range of 20-60 years. Breast-high ages of grand fir though were generally a few years younger.

Both the SH1 and CR1 model forms fit the data well with little difference between them throughout the data range. Examination of regeneration records from the Railroad Gulch research area on Jackson Demonstration State Forest indicated that the CR1 model form would extrapolate better in ages less than 15 years. This model, *GF_CR1_NC*, is considered to be the best that can be derived from the sample data. Parameter estimates are shown in table 6.10.

Grand Fir Comparisons and Evaluation

Relative to north coastal Douglas-fir site index curves, grand fir starts lower and catches up at about age 30. Figure 6.3 shows the *GF_CR1_NC* model and the *DF_KP1_NC* Douglas-fir model for comparative purposes. In the 30-60 years age range, curve shapes are virtually coincident. After age 60, grand fir site curves become flatter. This is an extrapolation beyond the range of available data. Virtually all potential sample trees 70 years of age and greater had either dead or broken tops. Comparative analysis with a limited number of samples from the FIA data set tends to support the observation that height growth of grand fir is less than Douglas-fir at ages over 70 years on comparable sites.

Grand Fir Summary and Recommendations

The *GF_CR1_NC* model is recommended for general use in estimating site index of grand fir in the Northern California Coast ecological section of California, particularly at breast-high ages less than 60 years. For breast-high ages of 30 to 60 years, Douglas-fir site index curves can be reasonably substituted. Care should be exercised in estimating grand fir site index with the *GF_CR1_NC* model for trees over 60 years of age, as it is an extrapolation beyond the sample data.

Table 6.9. Grand fir site index data summary.

Variable	Sample Statistics			Sample Size	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft)	87	23	38-165	Stands	36
Age (years)	30	11	15 - 64	Trees	41
Site Index(ft.)	132	16	117 - 154	Observations	96

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution.

Table 6.10. Statistical summary for the GF_CR1_NC grand fir site index model.

Model Name	Model Form	Solution Method	Parameter Estimates		RMSE (ft.)	R^2
			b_1	b_2		
GF_CR1_NC	CR1	IE	-0.03357	1.658	7.1	.999

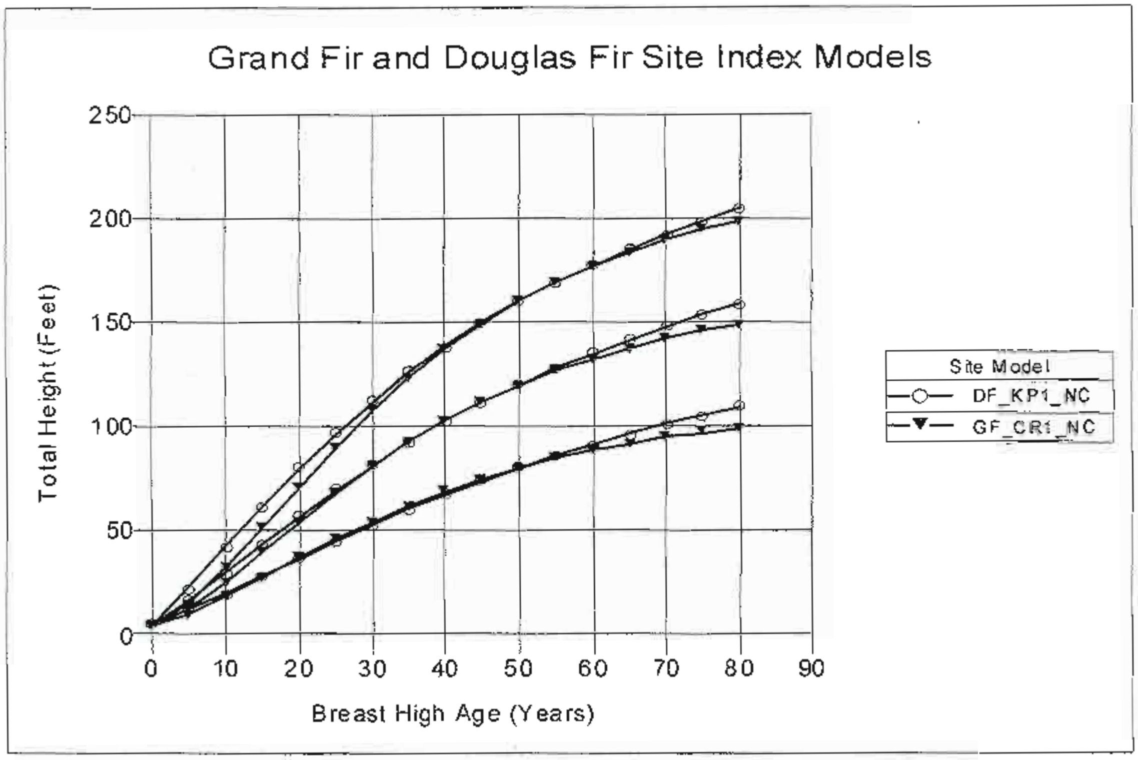

Figure 6.3. *Grand fir and north coastal Douglas-fir site index models.*

6.3.4 MC3 Species – Ponderosa Pine, Sugar Pine, interior Douglas-fir

Ponderosa pine has an extensive range in California and appears in all major ecological sections examined in this study. With the exception of the Northern California Coast ecological section, ponderosa pine is a primary commercial species and on suitable sites, is the artificial regeneration species of choice. Sugar pine and interior Douglas-fir fairly well match the range of ponderosa pine through mixed conifer zones but sugar pine does not appear in near the abundance. Neither of these two species appears much to the east of the general Sierra Nevada-southern Cascade crest and their distribution extends farther to the west than that of ponderosa pine.

Power's (1972a) examined several ponderosa pine site curves applicable to ponderosa pine in California (Dunning, 1942; Dunning and Reineke, 1933; Arvanitis et. al, 1964; Meyer, 1938). These curves were all constructed by guide curve methods. To various degrees, he found all of them to be somewhat lacking when compared to nine ponderosa pine stem analysis series.

MC3 Overview

As noted previously, clear distinctions in site curve shape between any of the three MC3 species has not been found. Attempts to isolate differences has been met with results of the same magnitude as found with a) comparing equally likely model forms with the same species, b) comparing data sources, or c) seemingly arbitrary partitions of the site tree data base. In several sub-analyses, two species (say ponderosa pine and sugar pine) were compared by only selecting stands where they both appeared. Apparent differences were significantly reduced. Thus, it appears that species is secondary to general site-specific effects in influencing shapes of MC3 species site index curves.

After a consideration of all factors, six site index models were constructed for MC3 species in California: Three species specific models for the main mixed conifer zone and three combined species models, one each for the main mixed conifer, other mixed conifer, and the McCloud area zones. All main mixed conifer zone models were based solely on stem analysis data, as sufficient amounts were available and reasonably spread out geographically to cover the age/site range of the resource. The combined MC3 species models for the other two zones utilized both stem analysis and growth plot data to balance the age/site distribution. Ponderosa pine comprised about 90 percent of the data from the McCloud area. On a tree basis, the other mixed conifer zone was made up of 75 percent interior Douglas-fir, 20 percent ponderosa pine, and 5 percent sugar pine. A data synopsis used in fitting these models is shown in tables 6.11 and 6.12.

Several model forms all appeared to be likely candidates but the CR2 model form consistently performed the best and was used for all MC3 site index models. For individual and combined species (PP, SP, DFI, MC3) from the main mixed conifer area, models were named *PP_CR2_MMC, SP_CR2_MMC, DFI_CR2_MMC*, and *MC3_CR2_MMC* respectively. The other mixed conifer and McCloud area zone models were named *MC3_CR2_OMC* and *MC3_CR2_MA* respectively.

Table 6.11. MC3 Individual species site index data summary for main mixed conifer zone stands. Stem analysis data only.

Variable	Sample Statistics			Sample Size	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Ponderosa pine					
Total Height(ft)	63	39	12 - 143	Stands	121
Age (years)	35	22	8 – 89	Trees	622
Site Index(ft.)	88	21	43 - 121	Observations	3876
Interior Douglas-fir					
Total Height(ft)	67	27	12 - 124	Stands	54
Age (years)	46	22	8 - 93	Trees	164
Site Index(ft.)	76	18	39 - 108	Observations	1087
Sugar Pine					
Total Height(ft)	60	26	12 – 119	Stands	49
Age (years)	43	21	11 - 83	Trees	101
Site Index(ft.)	72	20	42 - 118	Observations	618

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Table 6.12. Combined MC3 species site index data summary for all mixed-conifer zones.

Variable	Sample Statistics			Sample Size	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Main Mixed-Conifer *(stem analysis only)*					
Total Height(ft)	63	29	12 - 137	Stands	179
Age (years)	38	22	12 – 88	Trees	885
Site Index(ft.)	83	21	38 – 119	Observations	5562
Other Mixed-Conifer (*stem analysis and growth plot measurements)*					
Total Height(ft)	64	28	12 - 129	Stands	115
Age (years)	45	25	14 - 88	Trees	421
Site Index(ft.)	67	19	31 – 88	Observations	2114
McCloud Area *(stem analysis and growth plot measurements)*					
Total Height(ft)	69	34	14 – 135	Stands	68
Age (years)	43	24	8 – 92	Trees	256
Site Index(ft.)	84	14	47 – 107	Observations	1359

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

A statistical summary for all MC3 models is shown in table 6.13. Figure 6.4 shows the separate and combined species models for the main mixed conifer zone. Visually, there is not much difference between any of the separate species models and the combined model. Ponderosa pine is closest to the combined model largely reflecting the heavy weighting of PP observations in the database. Sugar pine is the most different but even at an extreme of 100 years on a high site of 120 – largely an extrapolation beyond available data limits – the difference in predicted site index is only six feet.

Ignoring the mixed conifer zones and fitting models to statewide data for MC3 species essentially replicated _MMC models. This is largely due to having the numbers of stands and trees from main mixed conifer areas dominate the database. Thus, the _MMC models should provide reasonable statewide representations.

Table 6.13 Statistical summary for the main mixed-conifer zone MC3 species site index models.

Model Name	Model Form	Solution Method	Parameter Estimates			RMSE (ft.)	R^2
			b_1	b_2	b_3		
PP_CR2_MMC	CR2	IE	-0.01441	-5.777	36.85	2.99	.997
DFI_CR2_MMC	CR2	IE	-0.01564	-6.260	38.98	3.45	.996
SP_CR2_MMC	CR2	IE	-0.01862	-9.153	54.31	1.67	.997
MC3_CR2_MMC	CR2	IE	-0.01524	-4.194	28.35	2.32	.997
MC3_CR2_MA	CR2	IE	-0.01267	-10.56	64.26	1.62	.998
MC3_CR2_OMC	CR2	IE	-0.01684	-1.255	12.53	1.93	.997

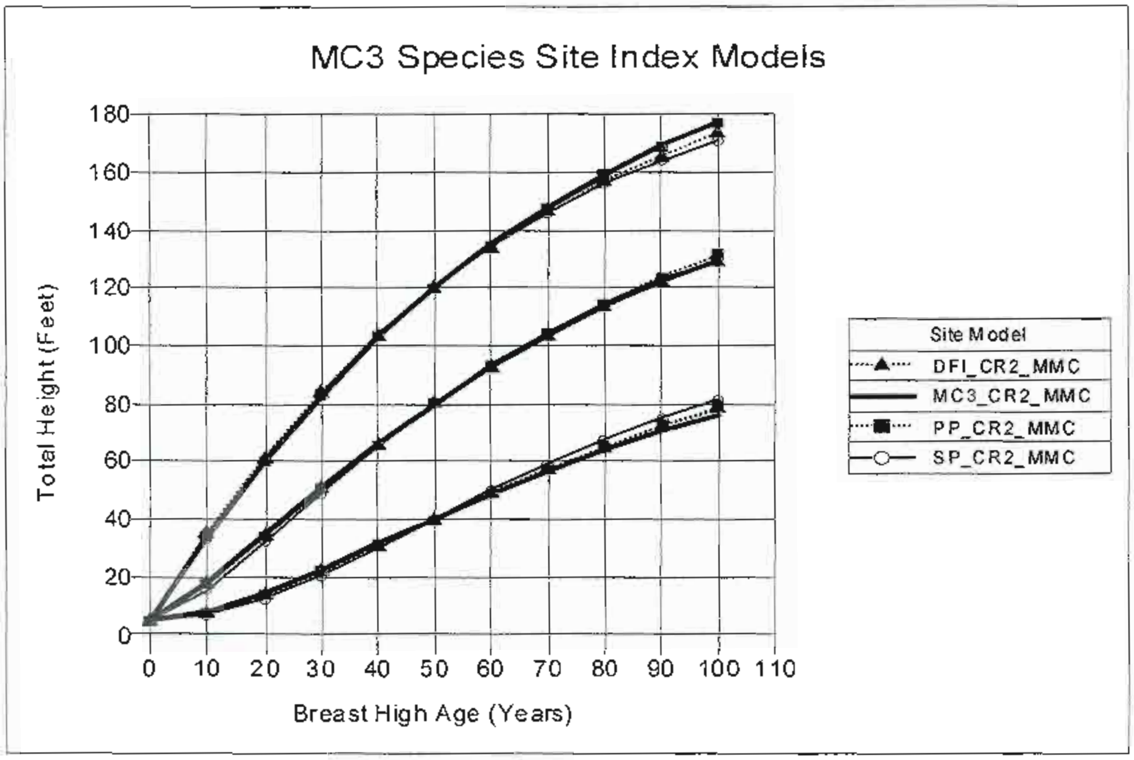

Figure 6.4. *MC3 species site index curves for the main mixed conifer zone.*

The combined MC3 species models for the three mixed conifer zones are shown in figure 6.5. Differences are most pronounced in older ages and can result in differences in site predictions of over one site class (20 feet of site index). For comparative purposes, site curves from these three models and the upper and lower 90 percent bounds from the random regression coefficient model described previously are shown in figure 6.6 for a site index of 70 feet. The MC3 models are well within the observed variation in the general statewide mixed conifer resource.

Each of the combined MC3 models was compared to stem analysis data from each of three mixed conifer zones and variance ratios were computed. These results are

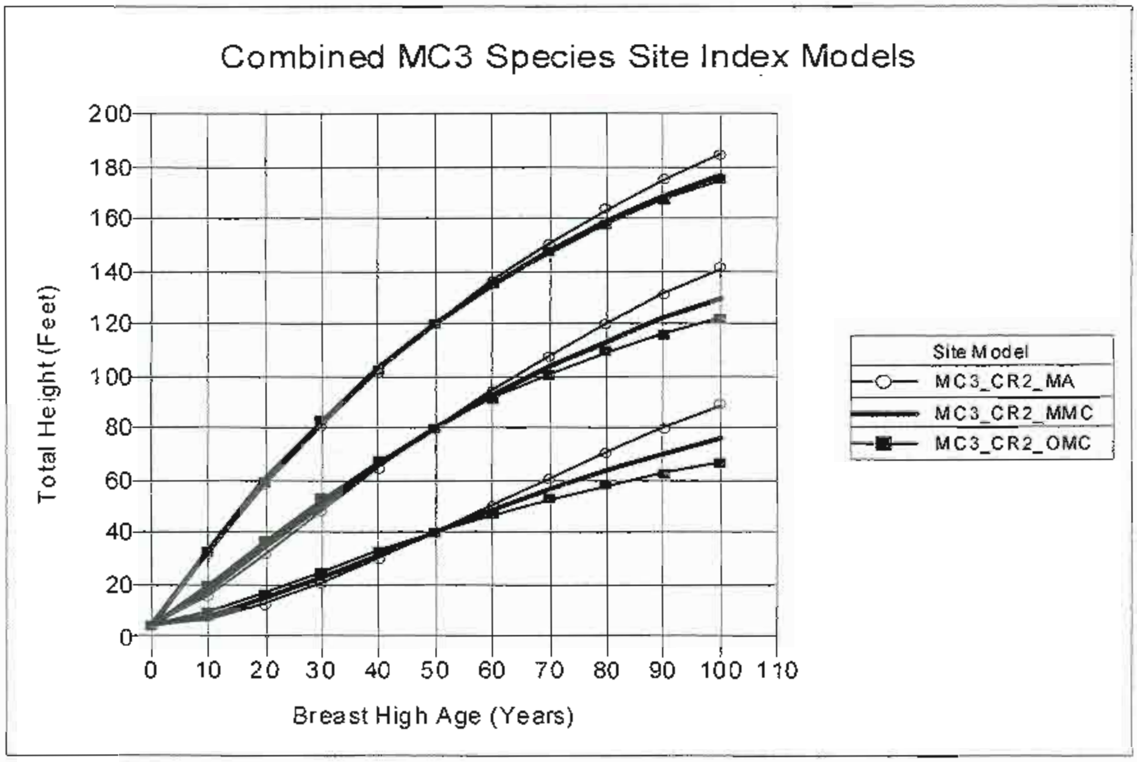

Figure 6.5. *Combined MC3 species site index models.*

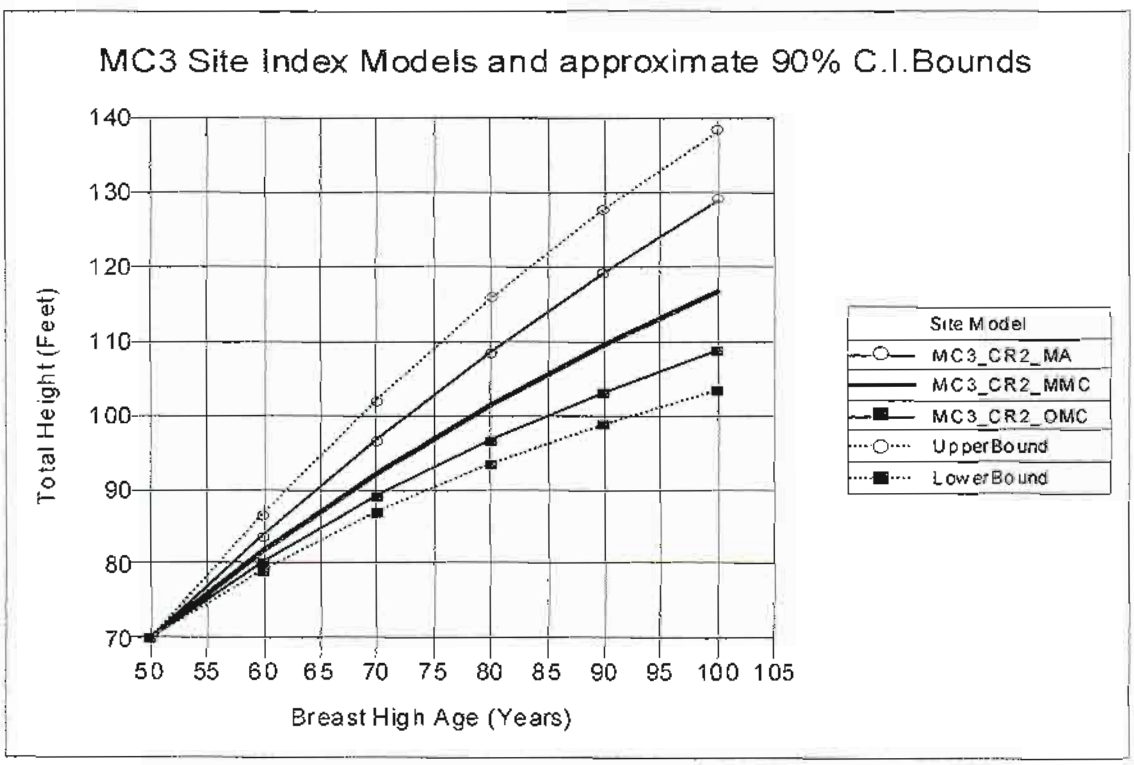

Figure 6.6. *MC3 site index models for a site index of 70 feet and approximate 90 percent confidence intervals.*

shown in table 6.14. It is apparent that the zonal models work best in their respective zones and precision gains can be achieved in site index estimation by adopting the broad based mixed conifer zonal classification developed here.

Table 6.14. MC3 variance ratios by data source zone.

Model	Data Source		
	Main Mixed Conifer	Other Mixed Conifer	McCloud Area.
MC3_CR2_MMC	1.00	1.16	1.33
MC3_CR2_OMC	1.28	1.00	2.41
MC3_CR2_MA	1.64	2.22	1.00
No. of Trees	603	159	116

The data used for the *MC3_CR2_OMC* model was largely interior Douglas-fir (75 percent), often growing in almost pure stands, and predominantly from the eastern sides of Northern California Coast Ranges and Klamath Mountains ecological sections. This model is practically coincident with the north coastal *DF_KP1_NC* Douglas-fir site index model. While being unconfirmed as data is lacking, either one of these models would appear to suffice as an MC3/Douglas-fir site model for the central and western portions of these two ecological sections.

MC3 Species Evaluations and Comparisons

Four existing site index models were compared with the *MC3_CR2_MMC* model using stem analysis data from the main mixed conifer zone described in table 6.11. These are Dunning and Reineke (1933), Dunning (1942), Biging and Wensel (1985), and the reconstituted breast-high age base model (*PP_PObha_1978)* derived from a subset of the data used by Powers and Oliver (1978) for their total age ponderosa pine site curves.

Figure 6.7 shows site curves from all these models bounding the general site index range found in the main mixed conifer data set. Variance ratios based on the main mixed conifer stem analysis data set relative to the *MC3_CR2_MMC* model are shown in table 6.15. Site prediction differences are shown in table 6.16.

Table 6.15. Variance ratios for selected candidate MC3 species site index models using the MC3_CR2_MMC model as a basis.

Model	Age-Site Class				
	Young/Low	Young/High	Old/Low	Old/High	Over All
MC_DR_1933	1.36	7.72	1.40	2.37	4.16
MC_Dunning1942	2.97	2.42	2.33	1.63	3.23
MC_BW_1985	1.44	3.98	1.20	1.92	2.37
PP_Pobha_1978	1.92	1.42	2.30	1.31	2.12
MC3_CR2_MMC	1.00	1.00	1.00	1.00	1.00
Trees (Obs.)	381(1827)	405(2151)	378(1375)	412(1062)	885(5562)

Table 6.16. Difference in main mixed conifer areas fir site index predictions (feet) from the MC3_CR2_MMC model by model, classification age and site index class.

Model	20 Years BHA			100 Years BHA		
	Site Index Class			Site Index Class		
	Low	Ave.	High	Low	Ave.	High
MC_BW_1986	2	11	26	5	2	-4
MC_DR_1933	-12	0	53	8	-1	-12
MC_Dunning_1942	-17	-19	-12	14	13	4
PP_Pobha_1978	-15	-12	10	14	10	1

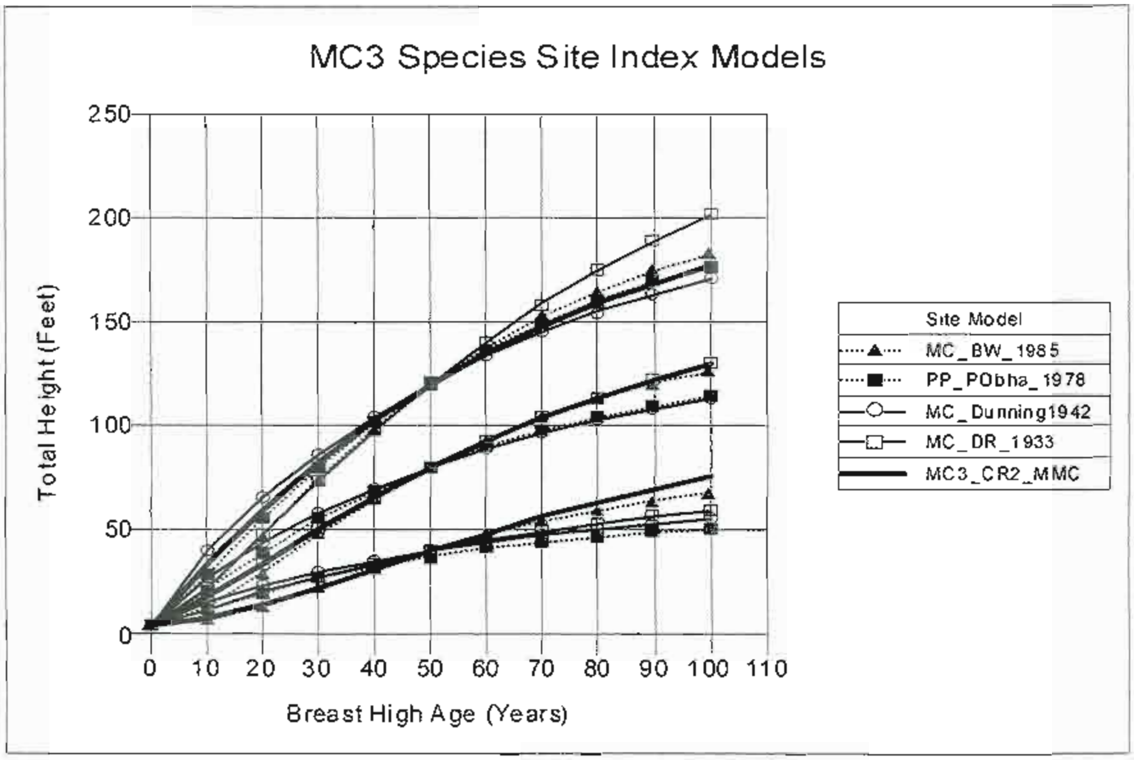

Figure 6.7. *MC3 species site index models.*

Obviously a well-constructed site index model from a specific data set, which is subsequently used as the comparative basis with other models, will usually perform the best. However, computing variance ratios with the NCPlot data set, which was not used in model construction, indicated results very consistent with those shown in table 6.15.

Dunning and Reineke's model universally performed the worst confirming Dunning's (1942) remarks that these curves "show absurd trends towards impossible heights at older ages".

Dunning's (1942) curves faired little better, being universally too flat compared to the data used in this study. Figure 6.8 shows the young growth portion of Dunning's site curves, adjusted to breast-high age, and a site curve generated by the *MC3_CR2_MMC* for an approximate mean site index of 70 feet. Assuming the *MC3_CR2_MMC* model is representative of MC3 species height growth development, site index predictions made from Dunning's curves are highly correlated with age at the time of classification. As can be seen from figure 6.8, predictions range from a site class V at about 10 years to a site class I at age 100. While possibly being adequate for old growth mixed conifer species, Dunning (1942) stated the opinion that his curves should probably be abandoned when emphasis in forest management changes to younger rotations.

The reconstituted *PP_PObha_1978* model also performs somewhat poorly. It is interesting to note however, that if comparisons are made based solely on the POPP data set from which this model was constructed, it is 36 percent more precise than the next closest model (*MM_CR2_MMC*). Site indices in this data set ranged from about 75 to 130 feet. Of the 16 available stands (90 trees), the lowest three by site index were from the Northern California Coast Ranges, the middle ten from the main mixed conifer zone, and the highest three were from the McCloud area. Thus, the site indices in this sample are correlated with the mixed conifer zonal classification, illustrating problems that can be expected from constructing regional mixed conifer site index models with small data sets.

Biging and Wensel's (1985) model performs reasonably well for ages over 50 but resulted in substantial overpredictions of site index when applied to young stands on better than average sites. This is felt to be due to the inclusion of a large proportion of white fir trees in the *MC_BW_1985* model. Their influence on the sigmoidal shape of the model is quite noticeable in younger ages. The data analyzed here suggests that the site curve shape of MC3 species is not nearly as sigmoidal as white fir.

MC3 Species Summary and Recommendations

The combined MC3 species site index models developed here appear to be the best regional site index models for ponderosa pine, interior Douglas-fir, and sugar pine and are recommended as replacements for other existing curves. There is little to suggest that specific models for any species in the MC3 group will do much better than combined models. The MC3_CR2_MMC model is recommended as the best all around statewide model for MC3 species. Separate MC3 models applicable to the three mixed conifer zones can increase the overall accuracy of site classification and are recommended for exclusive use in those areas. These models all have desirable base age invariant properties and can be used directly and consistently in both site index and height estimation.

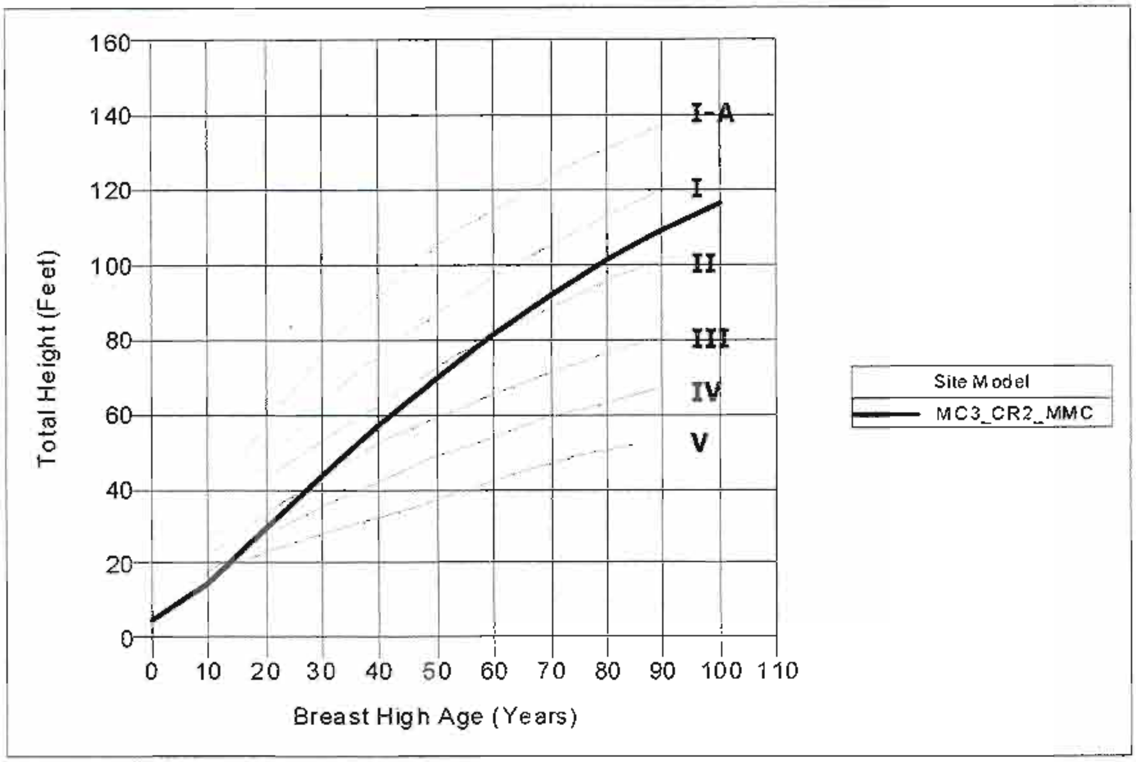

Figure 6.8. *MC3_CR2_MMC site curve for a site index 70 and Dunning's site curves adjusted to breast-high ages.*

6.3.5 White Fir

White fir is found primarily as a principal component of mid and higher elevation mixed conifer forest types and true fir forest types in the Sierra Nevada Mountains and the Southern Cascades. It also occurs in the Northern California Coast Ranges, the Klamath Mountains, and the Modoc Plateau. White fir was included in past mixed conifer site index studies (Biging, 1984; Biging and Wensel, 1985); Dunning and Reineke, 1933; Dunning, 1942) and species specific site curves were developed by Dolph (1987) and Schumacher (1926). Dolph found that his curves were substantially different from Schumacher's and recommended his as a replacement. Analysis here supports Dolph's conclusion that Schumacher's curves are a poor choice as a white fir site index basis.

White fir is problematic as a site species due to its ability to remain in less than 'free-to-grow' conditions for decades, still maintain thrifty tops and crowns, and then respond to eventual release. These situations are commonly associated with natural stands of white fir that have regenerated after fire events and grown up under brush understories or have been released in mixed conifer stands after the more valuable pines have been selectively harvested. It would appear that Schumacher's sample basis was influenced in this manner. In the quality assurance editing phase, twelve stands (clusters or sampling areas) were discarded as they showed abnormal growth acceleration after 40 years of age. Similarly, there are innumerable 70-plus years old white fir 'site trees' on some growth plots that appear to have very low site index yet are 'growing' like 30 year old trees. As the actual increment cores and complete management history of these trees were not available for scrutiny, there is no way of telling if the past environment of these trees were compatible with basic site tree requirements. As a consequence, only white fir stem analysis trees were used in model construction. Growth plot records were used as validation data.

A synopsis of stem analysis data used in model fitting is shown in table 6.17. There is an ample supply of white fir stem analysis data. An additional 894 trees from 444 growth plots were available for validation. White fir stem analysis data sources consisted of the NCStem, LDMC, LDRF, and GspWF data sets. By numbers of trees, the rough distribution by ecological section was:

44 percent - Sierra Nevada
50 percent - Southern Cascades
2 percent - Klamath Mountains
3 percent - Northern California Coastal Mountains
1 percent - Modoc Plateau

Initial analysis indicated that there were several factors associated with the shape of white fir site index curves (Type II polymorphism). It appears to do best on flat and northeast aspects in the 4500-6500 feet elevation range. Slight flattening of height growth development is noted on southwest aspects in the relatively lower elevation range of the species. Like the MC3 species, it does not do very well in the Northern California Coast Ranges. Attempts to discriminate however have shown results to be inconclusive. Consequently, one model was fit to all white fir stem analysis data available from all sources. The CR2 model form was considered the best and the resulting model is designated as *WF_CR2_Ca*. A statistical synopsis is shown in table 6.18.

Dolph (1987, 1991) developed separate site curves for white fir and red fir, which showed practical differences. Analysis here with independent datasets confirms these differences, so separate site curve systems for each of these two true fir species appears to be justified.

Table 6.17. White fir stem analysis site index data summary.

Variable	Sample Statistics			Sample Size	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft.)	63	26	13 - 107	Stands	167
Age (years)	46	20	8 - 88	Trees	897
Site Index(ft.)	73	14	42 - 101	Observations	8764

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Table 6.18. Statistical summary for the WF_CR2_Ca site index model.

Model Name	Model Form	Solution Method	Parameter Estimates			RMSE (ft.)	R^2
			b_1	b_2	b_3		
WF_CR2_Ca	CR2	IE	-0.02834	-4.336	31.51	4.1	.999

Evaluation and Comparisons

Variance ratios for several existing candidate white fir site index curves plus the *MC3_CR2_MMC* mixed conifer model as a comparative reference point are shown in table 6.19. Stem analysis data as summarized in table 6.17 was used for this purpose. Dunning's (1942) site index curves were the worst, followed by Dunning and Reineke's (1933) model. The *MC3_CR2_MMC* model also performed poorly, indicating that differences in top height development of MC3 species and white fir follow substantially different paths.

Figure 6.9 shows site curves of the models developed by Dolph (1987) and Biging and Wensel (1985), and the *WF_CR2_Ca* and *MC3_CR2_MMC* models developed here. Dolph's and Biging and Wensel's site index models are quite close to the WF_CR2_Ca model. Any of these site index models should reasonably characterize white fir in the 60-100 foot site index range where most white fir is found. Biging and Wensel's model is a little too steep in advanced ages on higher sites, which leads to underestimates of site index compared to the WF_CR2_Ca model. Dolph's model tends to be a little flat after 60-70 years of age. This is the upper limit of the age range of his data and the site curves beyond this age limit are largely extrapolations. His site curves actually reach maximums in the 100-130 year age range on higher sites and decrease thereafter. Thus, his admonition about an 80-year maximum age should be heeded. Dolph's model also has problems with site indices less than 50 feet in the 5-30 year age range. Heights are predicted in some cases to be less than 4.5 feet and in some places are negative. Dolph utilized Dahms' (1975) method in developing his white fir curves. Monserud (1984) also explored using this method for Douglas fir in Idaho. He found similar erratic behavior with his model at the edges of his data set and inferred it might be due to the highly over-parameterized model system that Dahms' method produces.

Table 6.19. Variance ratios for selected candidate white fir site index models using the WF_CR2_Ca model as a basis.

Model	Age-Site Class				
	Young/Low	Young/High	Old/Low	Old/High	Over All
MC_DR_1933	2.91	1.99	1.33	1.25	2.15
MC_Dunning_1942	7.44	7.61	3.37	2.27	6.86
MC_BW_1985	1.08	1.10	1.04	1.07	1.09
WF_Dolph_1987	1.07	1.14	1.05	1.18	1.15
MC3_CR2_MMC	1.46	2.25	1.02	1.12	1.60
WF_CR2_Ca	1.00	1.00	1.00	1.00	1.00
Trees (Obs.)	474(2534)	411(2895)	484(2584)	403(2177)	887(8420)

White Fir Summary and Recommendations

The WF_CR2_Ca model appears to be the best model that can be applied statewide to white fir in terms of precision and that has desirable base age invariant properties. Site curves of Biging and Wensel (1985) also appear to be a reasonable choice as a white fir site index curve. Site curves by Dolph (1987) are also reasonable but they should not be used below a site index of 50 feet or ages over 70-80 years.

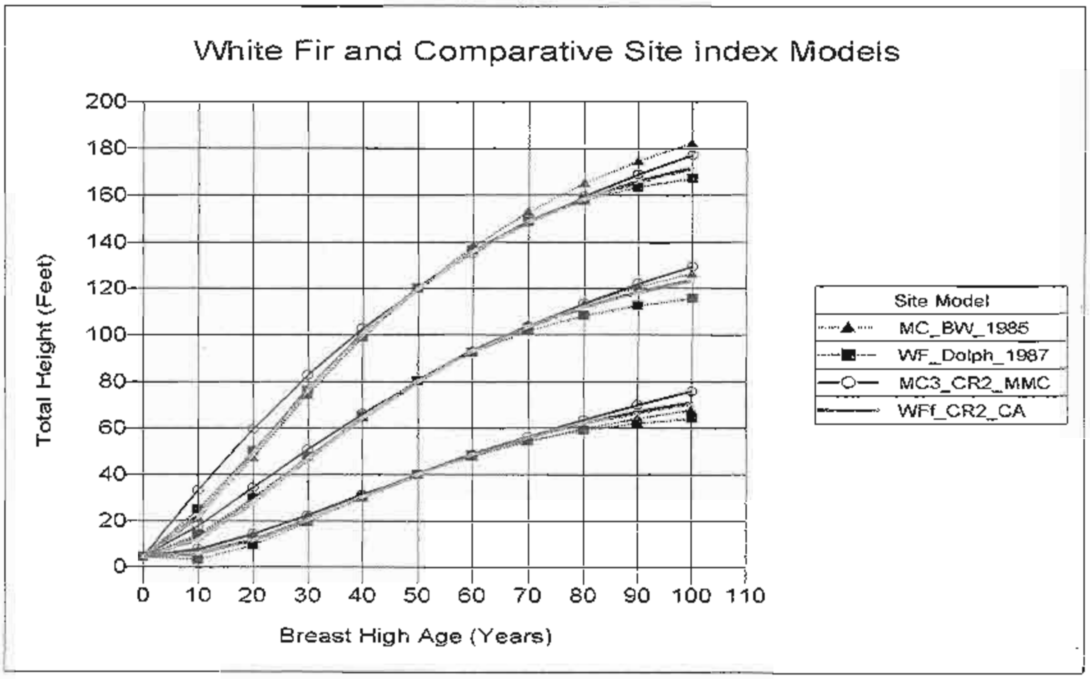

Figure 6.9. *White fir and comparative site index models.*

6.3.6 Red Fir

Red fir occurs primarily in true fir forest types at higher elevations in the Sierra Nevada and to a lesser extent in the Southern Cascades, the Klamath Mountains, and the Northern California Coast Ranges. Schumacher (1928) provided the earliest red fir site index curves. These were total age guide curves developed in conjunction with a normal yield study of red fir. Dolph (1991) developed new height prediction site index curves based on breast-high age and one dominant tree from each of 194 sample plots in 56 natural young-growth red fir sites in California and southern Oregon. The selected tree on each plot was in some sense the best growing tree. Dolph adjusted Schumacher's curves to breast-high ages and compared them with his new curves. He concluded they were substantially different. We concur with Dolph (1991) in that Schumacher's (1928) curves do not correspond well with red fir stem analysis and repeated height-growth measurements, and should not be used.

Red fir data available to this analysis consisted of the LDRF, NCPlot, and NCStem data sets. Initial analysis indicated that there were no location factors that seemed to influence the shape of red fir site curves in any appreciable manner. The relatively 'worse' places were in the Northern California Coast Ranges, the southern end of the red fir range in the Sierra Nevada, and on southwest slopes. These differences however were not significant. The arbitrary California-Oregon boundary line did not make any difference.

The *KP1* model form was found to be the best fit of the data. Combined stem analysis and growth plot data (with an age difference correction of .0077) indicated that there was no material difference in model fits through the stem analysis data range. As the growth plot data (38 stands, 89 trees, 247 measurements) filled in some higher sites and older ages, all data available was used to fit one red fir site index model applicable to the range of red fir in California: *RF_KP1_Ca*. A data and statistical summary are shown in tables 6.20 and 6.21 respectively.

Table 6.20. Red fir site index data summary.

Variable	Sample Statistics			Sample Size	
	Mean	**Std. Dev.**	**Range**[1]	**Source**	**Numbers**
Total Height(ft.)	50	36	10 - 118	Stands	93
Age (years)	48	22	8 - 101	Trees	404
Site Index(ft.)	55	16	29 – 78	Observations	2248

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Table 6.21. Statistical summary for the RF_KP1_Ca site index model.

Model Name	Model Form	Solution Method	Parameter Estimates			RMSE (ft.)	R^2
			b_1	b_2	b_3		
RF_KP1_Ca	CR2	IE	1.741	-110.3	20100	3.42	.998

Red Fir Comparisons and Evaluation

Dunning and Reineke (1933) included a small amount of red fir with their young-growth mixed conifer site curves while Dunning (1942) did not include any. Based on variance ratios, both of these models performed poorly, about on par with white fir comparisons. Neither is discussed further.

Three candidate red fir site index models were evaluated and compared with the *RF_KP1_Ca* model: Dolph's (1991) red fir model, Biging and Wensel's (1985) mixed conifer model which included a small amount of red fir data, and the *WF_CR2_Ca* white fir model to reference true fir species differences. Figure 6.10 shows site index curves at site index levels spanning the red fir data range. Table 6.22 shows variance based on all the data described in table 6.20. Table 6.23 shows differences in height predictions.

Table 6.22. Variance ratios for red fir site index models using the RF_KP1_Ca model as a comparison.

Model	Age-Site Class				
	Young/Low	Young/High	Old/Low	Old/High	Over All
MC_BW_1985	1.37	1.19	1.24	1.39	1.40
WF_CR2_Ca	1.19	1.03	1.13	1.22	1.21
RF_Dolph_1991	0.96	1.05	0.99	1.00	1.02
RF_KP1_Ca	1.00	1.00	1.00	1.00	1.00
Trees (Obs.)	167(755)	176(769)	192(741)	210(658)	402(2237)

Table 6.23. Difference in red fir site index predictions (feet) from the RF_KP1_Ca model by model, classification age and site index class.

Model	20 Years BHA Site Index Class (feet)			100 Years BHA Site Index Class (feet)		
	Low	Ave.	High	Low	Ave.	High
MC_BW_1985	2	-3	-3	5	2	-4
RF_Dolph_1991	2	0	1	0	1	-2
WF_CR2_Ca	7	3	0	2	8	4

Visually and by all diagnostics, there is no practical difference between Dolph's red fir model and the RF_KP1_Ca model. Both of these models are a little too steep for ages less than 10-12 years. This however is the lower boundary of the general applicable age range adopted for this study. The WF_CR2_Ca model and Biging and Wensel's (1985) model are in general too flat through the average red fir site index range of about 30-70 feet in older ages. These results are consistent with other independent red fir/white fir studies (Dolph, 1987, 1991). Independent treatment of both of these true fir species appears to be warranted.

Red fir Summary and Recommendations

Either the *RF_KP1_Ca* model developed here or Dolph's (1991) red fir model is recommended as a site curve basis for red fir in California. These models can be considered practically the same. Dolph's height prediction model cannot be solved for site index so machine processing requires either an iterative solution technique or tabular interpolation. The base age invariant *RF_KP1_Ca* model can be used directly for both height and site index prediction.

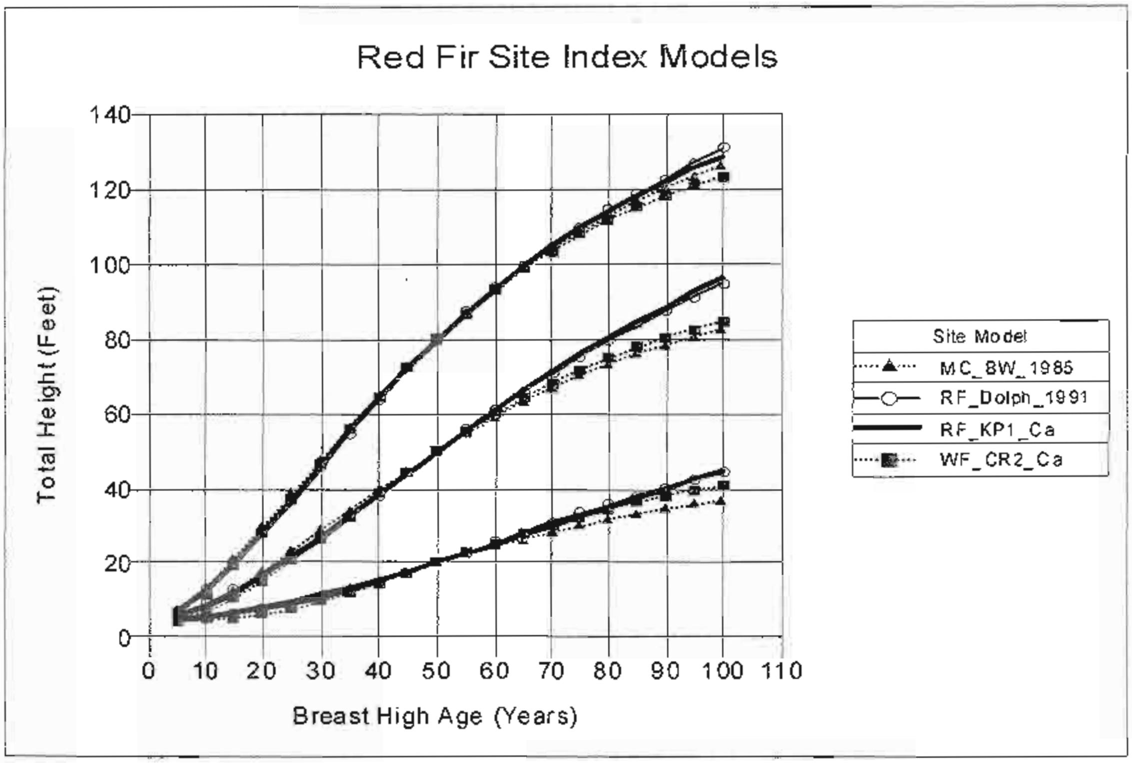

Figure 6.10. *Red fir site index models.*

6.3.7 Incense Cedar

Incense cedar is found throughout the mountain ranges of northern California in all of the ecological sections examined in this study but is primarily concentrated in mixed conifer forest types on the west slopes of the Sierra Nevada Mountains and the Southern Cascades. Isolated pockets occur on serpentine soils in the Northern California Coast ecological section. Incense cedar was not normally included in past mixed conifer site index studies. In Biging and Wensel's (1985) study, two of 343 trees were incense cedar, hardly making it a representative species. Species-specific site prediction curves were developed by Dolph (1983) based on 56 stem analysis trees from 55 growth plots located on the western slopes of the Sierra Nevada. Measurements were largely under 70 years of age.

In addition to the data used by Dolph (LDMC data set), the NCPlot, NCStem, and BFRS data sets were used as incense cedar data sources. Growth plot data was used to provide much needed observations in older age classes and higher sites. It amounted to about 25 percent of the total incense cedar data on a tree basis. The data is virtually all from the west slope of the Sierra Nevada Mountains and the Southern Cascades. A data synopsis is shown in Table 6.24.

While incense cedar is a common mixed conifer species, its site index is typically about 35 percent less than other conifer associates with about 80 feet being the maximum recorded in the data. Initial analysis also indicated that a family of straight lines, emanating from 4.5 feet, would be a reasonable site index model for incense cedar up to about 70 years of age. The logistic model form, LG1, proved to be the best fit and one model, named *IC_LG1_Ca*, was fit to all of the available incense cedar data. Post analysis did not indicate significant trends that could be attributable to ecological section, topographic position, or elevation. A statistical summary is shown in table 6.25.

Table 6.24. Incense cedar index data summary.

Variable	Sample Statistics			Sample Size	
	Mean	**Std. Dev.**	**Range**[1]	**Source**	**Numbers**
Total Height(ft.)	41	22	10 - 88	Stands	115
Age (years)	42	23	8 - 91	Trees	206
Site Index(ft.)	50	17	24 - 81	Observations	839

[1]Range is based on the means of the lowest and highest 10^{th} percentile of the distribution

Table 6.25. Statistical summary for the IC_LG1_Ca site index model.

Model Name	Model Form	Solution Method	Parameter Estimates			RMSE (ft.)	R^2
			b_1	b_2	b_3		
IC_LG1_Ca	LG1	IE	234.1	3.923	-1.237	2.78	.996

Incense Cedar Evaluations and Comparisons

Numerous existing site index equations and the newly developed base age invariant mixed conifer/true fir models previously described were compared with the incense cedar data described in table 6.24 and the IC_LG1_Ca model. None came very close in terms of variance ratios. The two closest models were the MC3_CR2_OMC model and the incense cedar site prediction model developed by Dolph (1983). Variance ratios and standard site prediction differences are shown in tables 6.26 and 6.27. Site curves spanning the sample range of incense cedar site index are shown in figure 6.11. All of these models are very similar under ages of 70 years, and under 85 years differences in predictions are less than five feet.

Table 6.26. Variance ratios for incense cedar site index models using the IC_LG1_Ca model as a basis.

Model	Age-Site Class				
	Young/Low	Young/High	Old/Low	Old/High	Over All
IC_Dolph_1983	0.94	1.69	1.12	1.33	1.32
IC_LG1_Ca	1.00	1.00	1.00	1.00	1.00
MC3_CR2_OMC	1.24	0.91	1.21	1.10	1.18
Trees (Obs.)	94(276)	68(269)	107(349)	99(264)	206(834)

Table 6.27. Difference in incense cedar site index predictions (feet) from the IC_LG1_Ca model by model, classification age and site index class.

Model	20 Years BHA			100 Years BHA		
	Site Index Class (feet)			Site Index Class (feet)		
	Low	Ave.	High	Low	Ave.	High
IC_Dolph_1983	-1	-3	1	5	7	1
MC3_CR2_OMC	3	0	-1	1	6	5

Incense Cedar Summary and Recommendations

Incense cedar should not be considered a component of any form of mixed conifer site classification system due to its generally lower site index when compared with other mixed conifer species. In the event that site index is required specifically for incense cedar, the *IC_LG1_Ca* model appears to be the best choice. The MC3_CR2_OMC model and Dolph's (1983) model are reasonable substitutes.

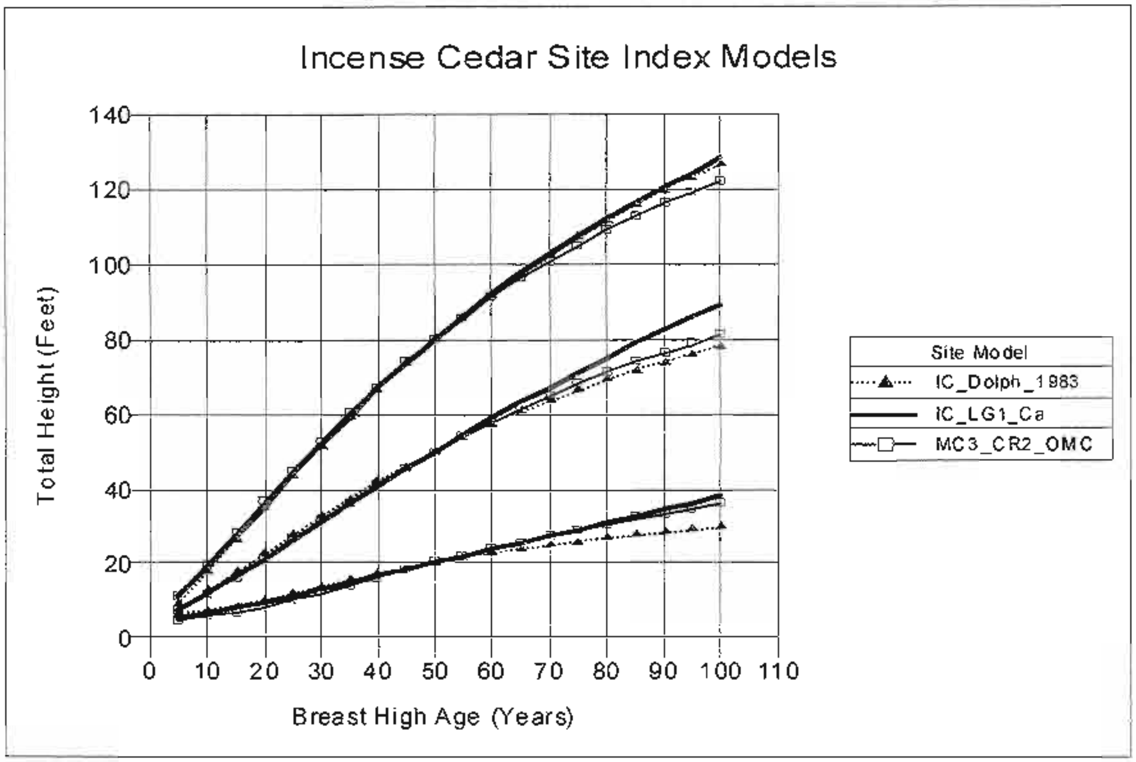

Figure 6.11. *Incense cedar site index models.*

6.3.8 Jeffrey Pine

Largely a California phenomenon, the range of Jeffrey Pine is fairly coincident with that of ponderosa pine, but at elevations less than about 5000 feet it only occurs on serpentine soils and outcrops. The normal pattern is for ponderosa pine to occur in mixed conifer forest types, gradually being replaced with Jeffrey pine at higher elevation true fir and subalpine forest types. Jeffrey Pine generally replaces ponderosa pine in southern California. No specific site index studies have been done for Jeffrey Pine.

Data available for Jeffrey Pine analysis is virtually all from single height/age measurements making the hardwood/minor conifer species (HMC) method the only option for fitting equations. Options available for the selection of the best model form is largely limited to comparing RMSE values of competing models and comparing fitted curves with like species such as ponderosa pine.

-The SH2 model form appeared to be well suited and one model, *JP_SH2_Ca*, was subsequently chosen as the best site index model available for all Jeffrey pine in California. A synopsis of the data used to fit the model and a statistical synopsis are shown in tables 6.28 and 6.29 respectively.

The *JP_SH2_Ca* model is almost indistinguishable from the other mixed conifer zone model (*MC3_CR2_OMC*). Attempts to fit the CR2 model form to Jeffrey pine data however, resulted in highly distorted curve shapes in the younger age classes. Both of these models and the data used to fit the *JP_SH2_Ca* model are shown in figure 6.12. Differences in site predictions from either of these models are at most four feet at ages of 20 and 100 throughout the sample site index range.

Table 6.28. Jeffrey Pine site index data summary.

Variable	Sample Statistics			Sample Sizes	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft)	52	23	16 – 93	Stands	39
Age (years)	62	23	26 – 96	Trees	374
Site Index(ft.)	45	17	22 - 81	Observations	374

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution.

Table 6.29. Statistical summary for the JP_SH2_Ca Jeffrey pine site index model.

Model Name	Model Form	Solution Method	Parameter Estimates				RMSE (ft.)	R^2
			b_1	b_2	b_3	b_4		
JP_SH2_Ca	SH2	HMC	0.3879	-1171	194.4	-0.3466	8.78	.991

Jeffrey Pine Summary and Recommendations

The JP_SH2_CA model is the only site index curve system available for Jeffrey pine in California. It is very similar to the MC3_CR2_OMC model and either one will suffice as a site index model for Jeffrey pine in California.

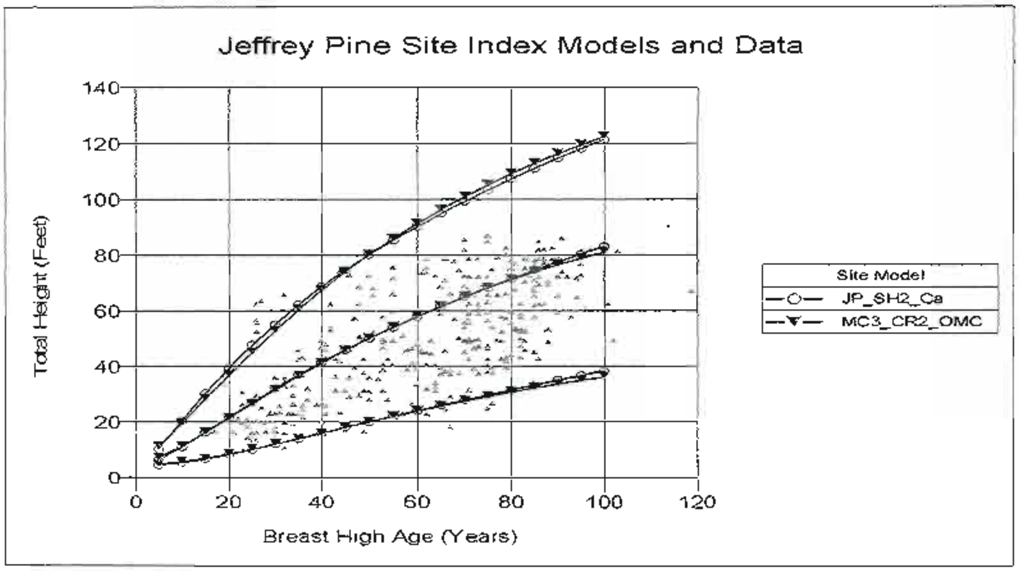

Figure 6.12. *Jeffrey Pine Site index models and data.*

6.3.9 Lodgepole Pine

Lodgepole pine is primarily concentrated at high elevations in the Sierra Nevada and Southern Cascades and is a component of the red fir/subalpine forest types. It also occurs at high elevations in lesser concentrations in the Klamath Mountains and the Modoc plateau (Warner Mountains). Subspecies (shore pine) also occur close to sea level in suitable environments in the Northern California Coast.

The data available for lodgepole pine site index modeling is scant and largely from high elevations in the Sierra Nevada mountains. Site indices were limited to a narrow band of 35 - 60 feet. The age range was about 20 – 120 years. The FIA data series contributed seven stands and 58 measurements. All other data sources contributed an additional six stands, 12 trees, and 39 measurements – about half stem analysis. All of this data was combined. The SH2 model fit by the HMC method gave the best results. Within the lodgepole pine sample site and age range, the resulting site curves provided an almost coincident overlay of the Jeffrey pine site index curves. Parameter estimates however, were highly different and extrapolations even slightly outside the data limits produced what were considered to be unrealistic curve shapes. The Jeffrey pine model appears to be a better choice.

Lodgepole Pine Summary and Recommendations

Either the *JP_SH2_Ca* Jeffrey pine model or the *MC3_CR2_OMC* model should provide a good characterization of lodgepole pine site index in California.

6.4 Hardwood Site Index Models

The data available for hardwood site index modeling largely consists of stands with five or more single height/age measurements on individual trees. The FIA data set supplied over 85 percent of these observations. The HMC solution method was used for all hardwood analysis. There were no stem analysis data available and what little repeated growth data that was available was retained as validation material.

6.4.1 Red Alder

Red alder is primarily a coastal species with major concentrations appearing in Humboldt and Del Norte counties. Primarily a riparian species, it can be an aggressive invader on disturbed soils in moist uplands within the fog belt in northern California.

Past studies of red alder site index in California are limited to Porter and Wiant (1965). They produced a 50-year *total age* based site prediction model of the form

$$H_s = H_0(.649 + 17.556/A_0)$$

Their model was based on 26 stem analysis trees sampled between 30 and 67 years of age with corresponding site indices in the range of 76 – 114. The average age of trees at breast height was one year. All of the samples were collected in Humboldt County. They noticed that their model produced coefficients that were virtually identical to those of Johnson and Worthington (1963) for red alder in the Pacific Northwest.

A 50-year age base height prediction model can be approximated from their model (*RA_PW_1965*) by assuming it takes one year to reach breast height. Performing basic algebraic operations gives the approximation

$$H = 4.5 + (H_s - 4.5)/(.649 + 17.556/(A+1))$$

Note that this model is only indicative, as a direct conversion of a total age to a breast-high age based system is not possible.

Data available for fitting red alder site index curves is relatively scant. A data summary is shown in table 6.30. Both a base age invariant equivalent of the *RA_PW_1965* model and the SH1 model form provided the best and virtually the same site curve families. The SH1 model form was retained and one model, *RA_SH1_Ca* was considered the best that could be extracted from the data. A statistical synopsis is shown in table 6.31.

Table 6.30. Red Alder site index data summary.

Variable	Sample Statistics			Sample Sizes	
	Mean	**Std. Dev.**	**Range**[1]	**Source**	**Numbers**
Total Height(ft)	62	15	35-93	Stands	14
Age (years)	28	8	16-58	Trees	90
Site Index(ft.)	75	16	45-102	Observations	114

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Table 6.31. Statistical summary for the RA_SH1_Ca red alder site index model.

Model Name	Model Form	Solution Method	Parameter Estimates		RMSE (ft.)	R^2
			b_1	b_2		
RA_SH1_Ca	SH1	HMC	-7.236	-0.7772	9.1	.96

Red Alder Evaluation and Comparisons

Figure 6.13 shows site curves for both the adapted *RA_PW_1965* model and the *RA_SH1_Ca* developed here along with the data used to fit the latter. Maximum differences in predicted site indices in the 60-100 foot range (where most of the sample data lie) between the two models are about five feet. Overall variance ratios differed by .01. Considering the relatively small and independent samples, the differences in types of measurements and estimation methods, and the general lack of validation data, there is little to suggest one model is better than the other.

Red Alder Summary and Recommendations

The previous curves of Porter and Wiant or the RA_SH1_Ca model developed here are not materially different from each other. Porter and Wiant's curves require an adjustment to be placed on a breast-high age basis. The RA_SH1_Ca model has desirable base age invariant properties and is more versatile for computational purposes.

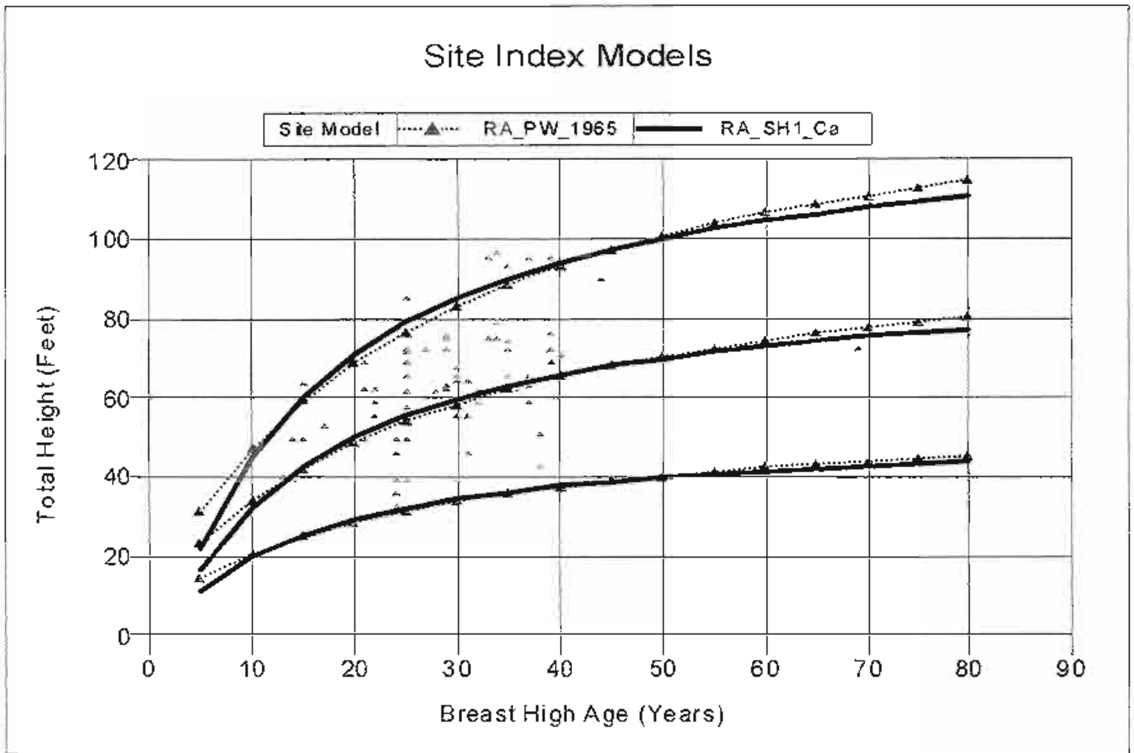

Figure 6.13. *Red alder site index models and data.*

6.4.2 Madrone

Main concentrations of madrone in California appear in the North and Central Coast, frequently as an associate in redwood – Douglas-fir forest types. Scattered populations also appear in the Klamath Mountains, Southern Cascades and the Sierra Nevada ecological sections. It appears in moister oak woodland forest types and is an associate species in lower elevation mixed-conifer forests.

Past studies of madrone site index in California are limited to Porter and Wiant (1965). They produced a 50-year *total age* based site prediction model of the form

$$H_s = H_0(.375 + 31.233/A_0)$$

Their model was based on 25 stem analysis trees sampled between 28 and 71 years of age with corresponding site indices in the range of 53 – 95. The average age of trees at breast height was 2.8 years. All of the samples were collected in Humboldt County.

A 50-year age base height prediction model can be approximated from their model (*MD_PW_1965*) by assuming it takes 2.8 years to reach breast height. Performing basic algebraic operations gives the approximation

$$H = 4.5 + (H_s - 4.5)/(.375 + 31.233/(A+2.8))$$

As with red alder, this model is only indicative as a direct conversion of a total age to a breast-high age based system is not possible.

A summary of data available for fitting Madrone site index curves is shown in table 6.32. The data is virtually all from the coastal ecological sections. The data here is much more extensive than that of Porter and Wiant, spanning a wider age and site range although the average site index is about 20 feet less. The SH1 model form provided the best fits of several tried, both in RMSE and reasonableness of fits in the younger age classes. The explicit model, *MD_SH1_Ca* was considered the best that could be extracted from the data. A statistical synopsis is shown in table 6.33.

Table 6.32. Madrone site index data summary.

Variable	Sample Statistics			Sample Sizes	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft)	52	18	24 - 85	Stands	54
Age (years)	60	25	22 - 101	Trees	418
Site Index(ft.)	50	15	27 - 81	Observations	418

[1]Range is based on the means of the lowest and highest 10^{th} percentile of the distribution

Table 6.33. Statistical summary for the MD_SH1_Ca madrone site index model.

Model Name	Model Form	Solution Method	Parameter Estimates		RMSE (ft.)	R^2
			b_1	b_2		
MD_SH1_Ca	SH1	HMC	-5.3508	-0.3883	9.2	.97

Madrone Evaluations and Comparisons

Figure 6.14 shows site curves for both the *MD_PW_1965* model and the *MD_SH1_Ca* developed here along with the data used to fit the latter. As a whole, these curve families are almost coincident up to about age 50. In older ages, the curves developed here are flatter. For a site index of 80 feet, maximum differences in predicted site indices are about eight feet at 100 years. Part of this difference is due to the approximate Porter and Wiant model used for age compatibility. Also noted is that a base age invariant equivalent of Porter and Wiant's model was tried and although the curve system was closer to that of the *MD_PW_1965* model, the RMSE was about 20 percent higher than the SH1 model form adopted here. This suggests that the model form adopted by Porter and Wiant may not be optimal for madrone. Comparisons of variance ratios indicated maximum differences of .05 or less for any age/site quadrant and .01 overall. Other than noting that the *MD_SH1_Ca* model had much more data in the 60-plus age range than the previous study and presumably provides a better fit in that age range, there is little basis to suggest one model is better than the other.

Madrone Summary and Recommendations

There is little basis to suggest that either the previous curves of Porter and Wiant or the *MD_SH1_Ca* model developed here are materially different from each other. Porter and Wiant's curves require an adjustment to be placed on a breast-high age basis. The MD_SH1_Ca model has desirable base age invariant properties and is more versatile for computational purposes.

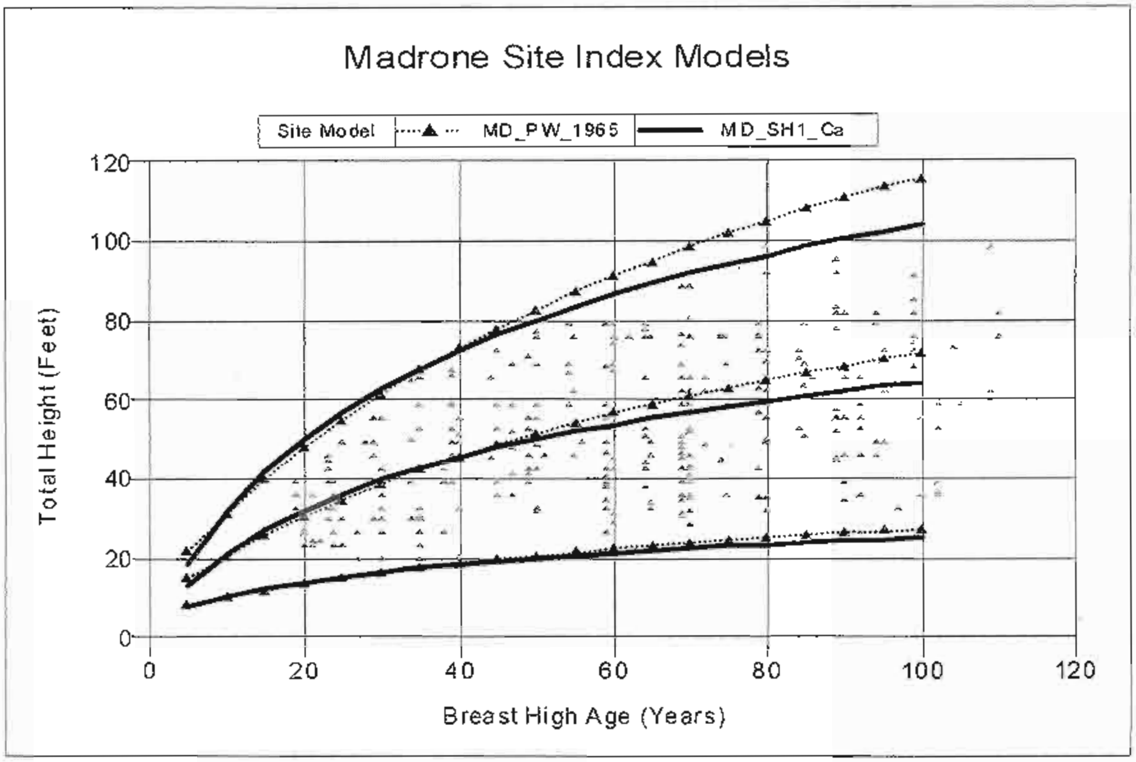

Figure 6.14. *Madrone site index models and data.*

6.4.3 Tanoak

Main concentrations of tanoak in California appear in the North and Central Coast, frequently as an associate in redwood – Douglas-fir forest types. Scattered populations also appear in the Klamath Mountains, Southern Cascades and the Sierra Nevada ecological sections.

Past studies of tanoak site index in California are limited to Porter and Wiant (1965). They produced a 50-year *total age* based site prediction model of the form

$$H_s = H_0(.204 + 39.233/A_0)$$

Their model was based on 30 stem analysis trees sampled between 32 and 71 years of total age with corresponding site indices in the range of 47 – 86. The average total age of trees at breast height was 3.2 years. All of the samples were collected in Humboldt County. A 50-year age base height prediction model can be approximated from their model (TO_*PW_1965*) by assuming it takes 3.2 years to reach breast height. Performing basic algebraic operations gives the approximation

$$H = 4.5 + (H_s - 4.5)/(.204 + 39.787/(A+3.2))$$

As with red alder this model is only indicative, as a direct conversion of a total age to a breast-high age based system is not possible.

A synopsis of data available for fitting tanoak site index curves is shown in table 6.34. The data is virtually all from the Northern California Coast ecological section. The data here is much more extensive than that of Porter and Wiant, spanning a much wider age and site range although the average site index is about 15 feet less. The CR1 model form provided the best fits of several tried, both in RMSE and reasonableness of fits in the younger age classes. The explicit model, *TO_CR1_Ca* was considered to be the best. A statistical synopsis is shown in table 6.35.

Table 6.34. Tanoak site index data summary.

Variable	Sample Statistics			Sample Sizes	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft)	54	21	22 - 92	Stands	144
Age (years)	50	24	21 – 99	Trees	1615
Site Index(ft.)	55	16	29 – 83	Observations	1618

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Table 6.35. Statistical summary for the TO_CR1_Ca tanoak site index model.

Model Name	Model Form	Solution Method	Parameter Estimates		RMSE (ft.)	R^2
			b_1	b_2		
TO_CR1_Ca	CR1	HMC	-0.007455	0.7743	10.7	.96

Tanoak Evaluations and Comparisons

Figure 6.15 shows site curves for both the TO_PW_1965 model and the *TO_CR1_Ca* developed here along with the data used to fit the latter. Much the same as madrone, the curves developed here are flatter than previous ones. Also noted is that a base age invariant equivalent of Porter and Wiant's model was tried and although the curve system was closer to that of the TO_*PW_1965* model, the residual variance was about 30 percent higher than the CR1 model form adopted here. This suggests that the model form adopted by Porter and Wiant may not be optimal for tanoak. Other than noting that the TO_*CR1_Ca* model had much more data in the 60+-age range than the previous study and presumably provides a better fit in that age range, there is no other available basis for comparison.

Tanoak Summary and Recommendations

There is little basis to suggest that either the previous curves of Porter and Wiant or the *TO_CR1_Ca* model developed here are materially different from each other. Porter and Wiant's curves require an adjustment to be placed on a breast-high age basis that will not be straightforward. The *TO_CR1_Ca* model has desirable base age invariant properties and is more versatile for computational purposes.

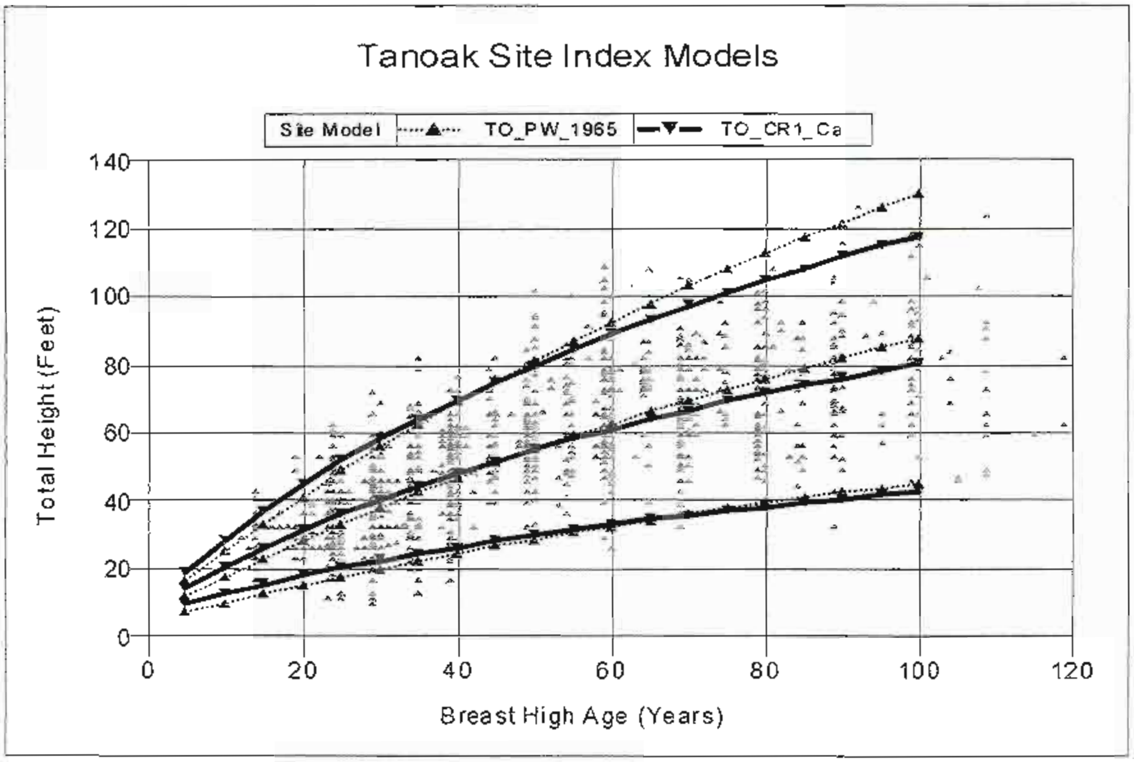

Figure 6.15. *Tanoak site index models and data.*

6.4.4 Black Oak

Black oak is wide spread in California. Large concentrations appear in the Northern California Coast, North Coast Coastal Mountains, Klamath Mountains, Southern Cascades and the Sierra Nevada ecological sections. It is a common associate in lower elevation mixed conifer forests and also appears on the drier east side of the Northern California Coast.

Past studies of black oak site index are limited to those of Powers (1972b). Dominant sprouts in 67 even-aged black oak stands were sampled for single height/breast-high age measurements. Locations were primarily on the west side of the Northern Sierra Nevada ecological section. Locations were stratified by adjacent ponderosa pine site index to minimize possible site-age correlation problems. While not stated, it appeared from graphics that most of the sample location site indices were in the 50-60 foot range with a few in the 40-50 foot range. Powers developed a 50-year breast-high site prediction model of the form

$$H_s = \frac{H_0 + 6.413(\sqrt{A_0} - \sqrt{50})}{1 + 0.322(\sqrt{A_0} - \sqrt{50})}$$

that can be transformed into a height prediction model by basic algebraic operations. This model is denoted as *BO_Powers_1972*. Power's notes his site curves should not be used for trees less than 20 years breast-high age.

Data available for black oak site index analysis was drawn from 63 statewide locations. Over 65 percent were from black oak as an associate in mixed conifer stands. A data synopsis is provided in table 6.36.

Table 6.36. Black oak site index data summary.

Variable	Sample Statistics			Sample Sizes	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft)	54	21	19 – 85	Stands	63
Age (years)	64	24	24– 104	Trees	478
Site Index(ft.)	43	19	19 –67	Observations	478

[1]Range is based on the means of the lowest and highest 10^{th} percentile of the distribution

Several model forms produced comparable RMSE values. The LG1 model form appeared to extrapolate better beyond the basic age/site range of the data. Consequently, the LG1 model form was fit to the data and the resulting model, *BO_LG1_Ca* was considered to be the best BAI model for black oak that could be extracted from the data. A statistical synopsis is shown in table 6.37.

Table 6.37. Statistical summary for the BO_LG1_Ca black oak site index model.

Model Name	Model Form	Solution Method	Parameter Estimates			RMSE (ft.)	R^2
			b_1	b_2	b_3		
BO_LG1_Ca	LG1	HMC	233.4	4.984	-1.016	9.3	.96

Black Oak Evaluations and Comparisons

Site curves for both the *BO_Powers_1972* and the *BO_LG1_Ca* model are shown in figure 6.16 along with the data used to fit the latter. Both of these curves are quite compatible in the 45-65 foot site index range at ages over 30 years. This is somewhat remarkable considering the differences in stand conditions and site tree selection rules, models forms, and methods. Below 30 years of age, Powers' curves (Powers, 1972b) performed poorly and, as he cautions, should not be used below an age of 20 years. His site curves all intersect at an approximate age of 17 years. Power's site curves also performed poorly below site indices of 40. These site curves become horizontal lines at a site index of 20 and indicate negative growth at lesser site indices.

Black Oak Summary and Recommendations

Both the *BO_Powers_1972* and the *BO_LG1_Ca* appear to be reasonable black oak site index curves in the approximate 45-65 foot site index range at ages 30 years and greater. Caution should be exercised in using Power's black oak site curves outside of this age/site range. The *BO_LG1_Ca* model appears to extrapolate much better outside these ranges and is recommended for a general statewide black oak site index model.

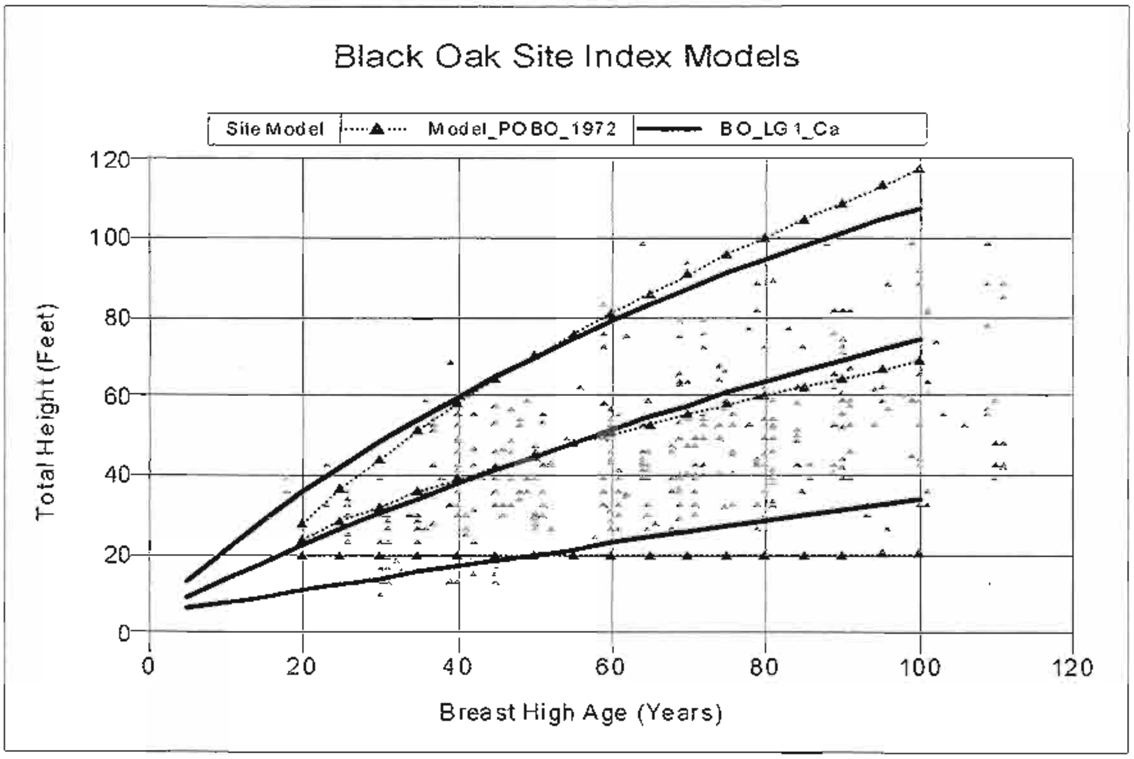

Figure 6.16. *Black oak site index models and data.*

6.4.5 Other Oaks

True oaks other than black oak are wide spread in northern California. Major concentrations occur throughout the Northern California Coast Ranges, the Klamath Mountains, and oak woodlands and lower elevation drainages surrounding the Sacramento valley.

Previous studies of other oaks site index (Delasaux and Pillsbury, 1987) have been confined to blue oak (*BLO_DP_1987*) and coast live oak (*LO_DP_1987*) in Monterey and San Luis Obispo counties. They used the technique described by Dahms(1975) to fit site prediction equations ($S = f(H, A)$). Twenty-five plots were established in pure stands of each species. Two to four trees that were the tallest on each plot at the time of sampling were chosen for stem analysis. Observations from the tallest tree at each decade beginning at age 20 were retained for subsequent analysis. Thus the resulting site curves are designed to predict site index from the tallest tree on a plot and do not quite represent a site curve system designed to predict the average height trajectory of site trees.

In this study, data from five major oak species (California live oak, Oregon white oak, blue oak, interior live oak, canyon live oak) with enough data to warrant investigation were analyzed. All of this data came from the FIA data set and the HMC solution method was used to derive site curve coefficients. Due to the similarity in height development between species and the relatively coarse nature of the data, we were not able to sufficiently discriminate between species and other classification variables to warrant developing separate site index curve systems for specific oak situations. Consequently, all other oak data were combined into one composite for site index analysis. The geographic range of this data was extensive and covered 39 counties within the State (see Appendix I). The anamorphic SH1 model form fit the data the best and a composite model, *OO_SH1_Ca*, was deemed applicable to all oaks other than black oak in California. A data synopsis is shown in table 6.38 and a statistical synopsis is given in table 6.39.

Table 6.38. Other Oaks site index data summary.

Variable	Sample Statistics			Sample Sizes	
	Mean	**Std. Dev.**	**Range**[1]	**Source**	**Numbers**
Total Height(ft)	32	12	12 - 106	Stands	228
Age (years)	61	23	22– 107	Trees	2025
Site Index(ft.)	30	10	14 - 53	Observations	2025

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Table 6.39 Statistical summary for the OO_SH1_Ca other oaks site index model.

Model Name	Model Form	Solution Method	Parameter Estimates		RMSE (ft.)	R^2
			b_1	b_2		
OO_SH1_Ca	SH1	HMC	-6.455	-0.3725	6.3	.96

The *OO_SH1_Ca* model is shown in figure 6.17 along with madrone and black oak site index models and the data used in fitting. As is evident from examination, madrone and other oaks have almost the same height growth patterns after age 20. Black oak however, is materially different.

Other Oak Evaluations and Comparisons

The OO_SH1_Ca model is shown in figure 6.18 and 6.19 along with the *BLO_DP_1987* and *LO_DP_1987* models of Delasaux and Pillsbury (1987). Several things are worth noting. The latter two models (DP models) were fit to data from 20 – 100 years in breast-high age. Coast live oak mean sample site index was 37 feet and blue oak was 21 feet. The range in applicability of both models in terms of age and site index was not explicitly stated. In our data set, blue oak site index ranged from 15 - 40 feet and live oak site index from 25 – 65 feet.

As evidenced from both figures, the DP models behave erratically below 20 years of age. On low sites, both models predict heights less than 4.5 feet somewhere between 0 and 20 years and the blue oak model has a discontinuity at 14.67 years. It is apparent that neither of these models should be used below 20 years of age. Also noted is that the *LO_DP_1987* model indicates that height growth achieves a minimum in the 70-90 year age range for site indices less than 30 feet and increases thereafter. Conversely, the BLO_DP_1987 model indicates minimum height growth in the 50-90 year age range for site indices greater than 35 years. As noted previously, this behavior is probably due to utilizing Dahms' method in estimation.

In spite of these problems, there is not much difference between any of the oak models in the 30 – 80 year age range over the site ranges likely to be encountered in practice. We would expect the DP models to be steeper as they are based on the tallest trees on a plot at each decade rather than average trajectories of all sample trees.

Other Oak Summary and Recommendations

The OO_SH1_Ca model is well behaved and has desirable base age invariant properties. It is also consistent with the site tree concept adopted elsewhere in this study. It would appear to be a good choice as an all around oak site index model in the State.

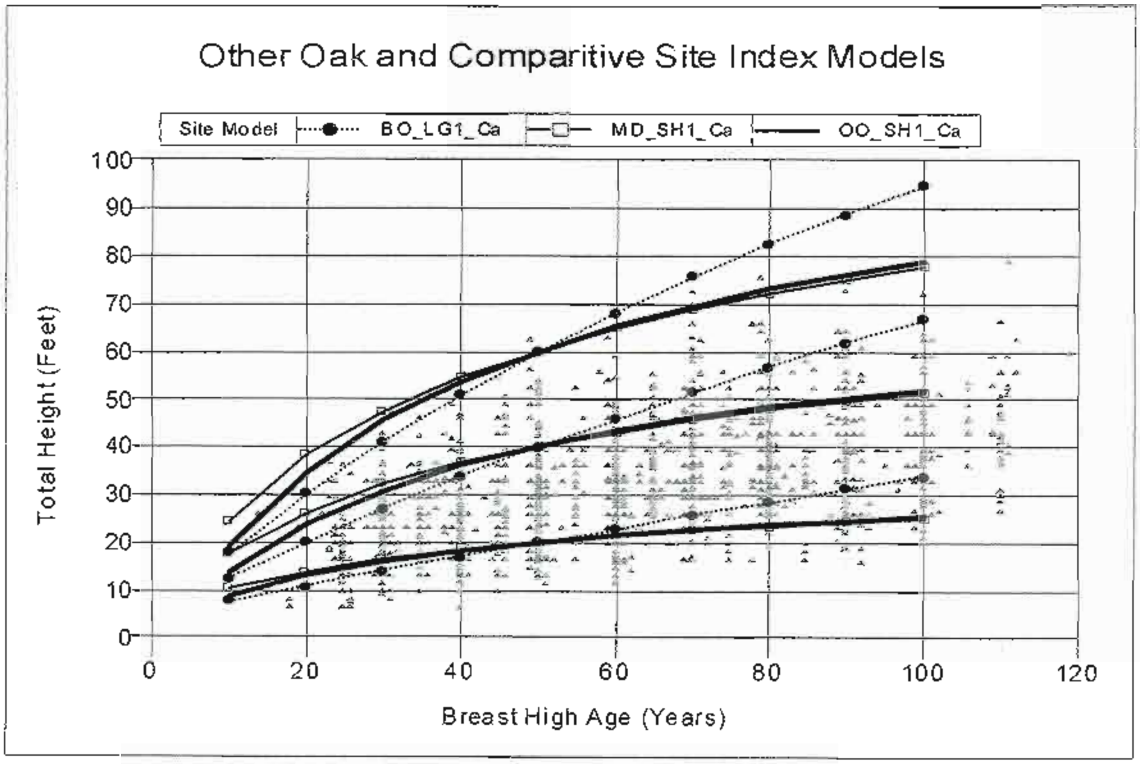

Figure 6.17. *Other oak and comparative species site index models and data.*

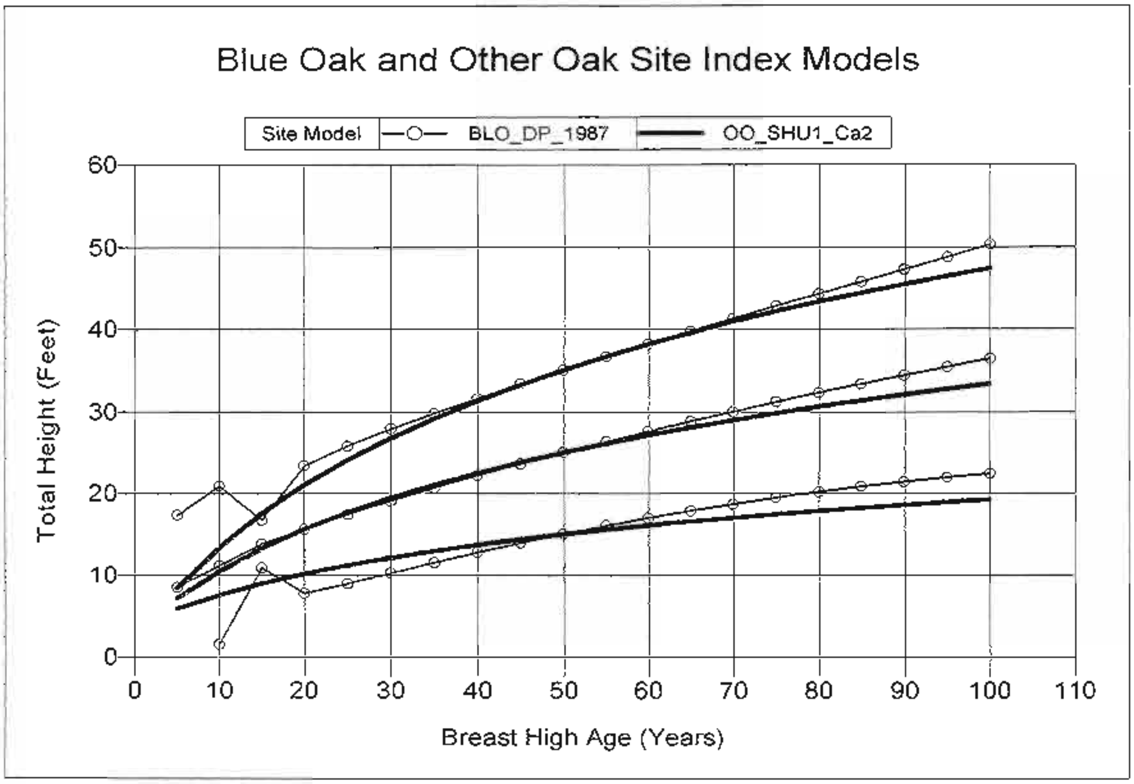

Figure 6.18. *Blue oak and other oak site index models.*

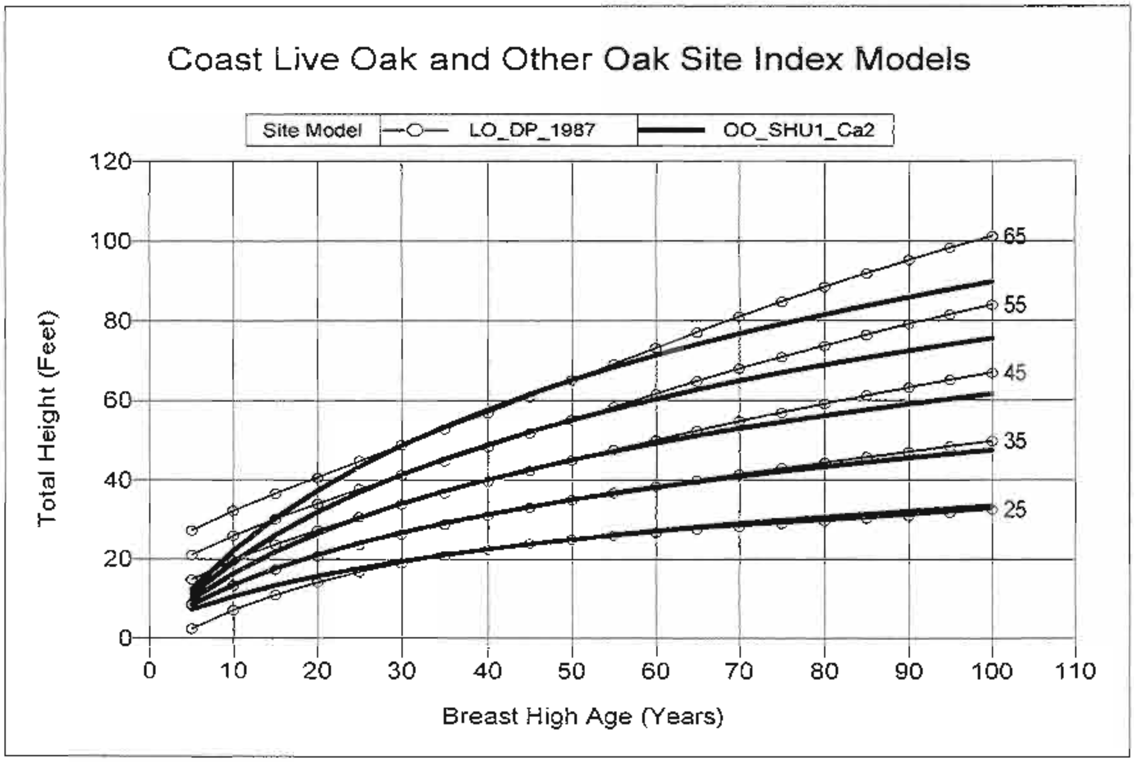

Figure 6.19. *Coast live oak and other oak site index models.*

6.4.6 California Laurel

California laurel (bay) is mainly concentrated in the Northern and Central California Coast ecological sections. It also has a fairly scattered but widespread distribution in interior California but seldom as an associate in commercial forest timber types. No site curves for this species have been constructed previously.

While data available to analyze California laurel is fairly scant, reasonable fits were obtained. Virtually all of the data came from the Northern California Coast. The SH1 model form was in some sense the best and one model, *CL_SH1_Ca*, was considered the best that could be extracted from the data. A data synopsis is shown in table 6.40 and a statistical synopsis is given in table 6.41.

Table 6.40. California laurel site index data summary.

Variable	Sample Statistics			Sample Sizes	
	Mean	Std. Dev.	Range[1]	Source	Numbers
Total Height(ft)	50	19	23 - 91	Stands	19
Age (years)	56	20	29 - 92	Trees	133
Site Index(ft.)	30	10	28 - 69	Observations	133

[1]Range is based on the means of the lowest and highest 10th percentile of the distribution

Table 6.41. Statistical summary for the CL_SH1_Ca California laurel site index model.

Model Name	Model Form	Solution Method	Parameter Estimates		RMSE (ft.)	R^2
			b_1	b_2		
CL_SH1_Ca	SH1	HMC	-99.58	-0.007382	6.2	.98

The *CL_SH1_Ca* model was very similar to that developed for tanoak and both are shown in figure 6.20 along with the data used to fit the California laurel model.

California Laurel Summary and Recommendations

As no other site index curves exist, the *CL_SH1_Ca* model is recommended as a general site index basis for California laurel.

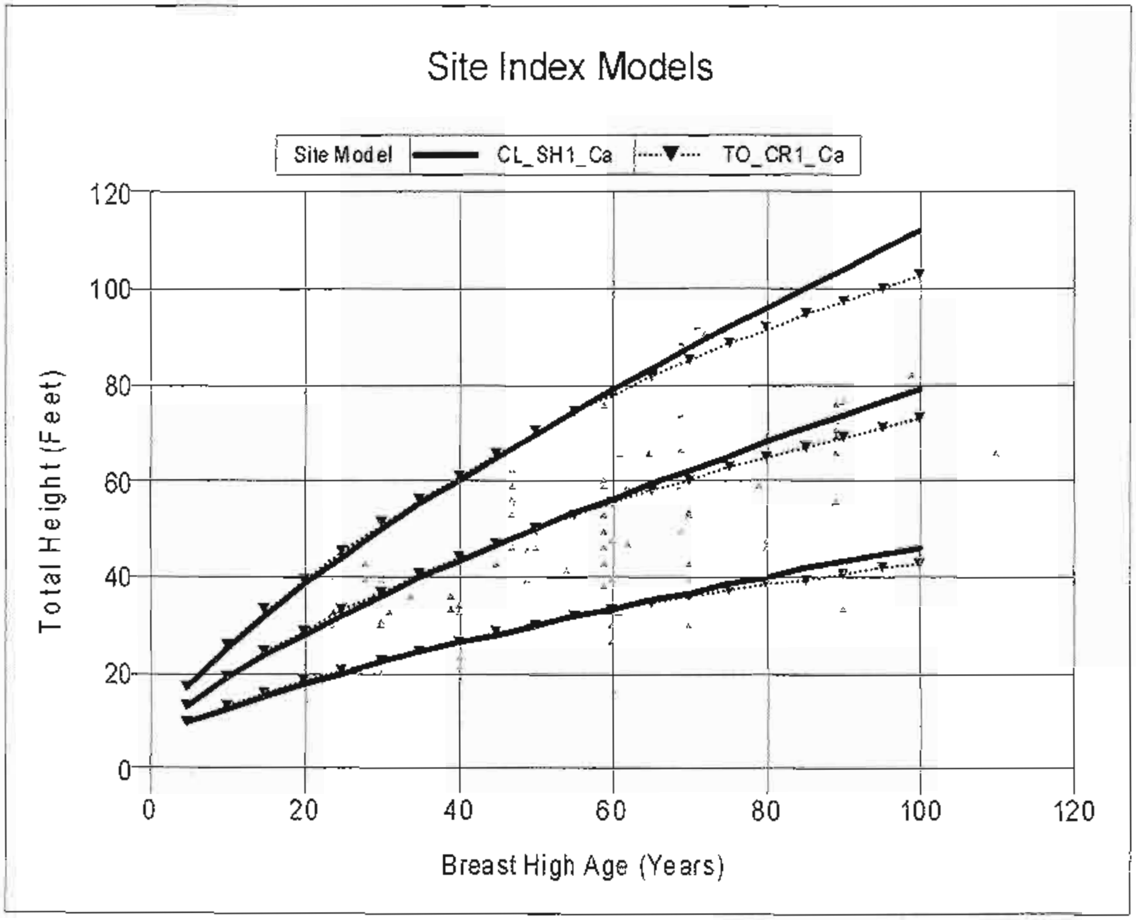

Figure 6.20. *California laurel and tanoak site index models and data.*

7. Intra-Stand Species Site Index Relationships

Indirect site index estimates for individual species that have not been sampled are sometimes necessary, for example, to serve as input to growth models such as CRYPTOS and CACTOS (Wensel, et al. 1987, 1986). Prediction equations are developed here for this purpose.

7.1 Past Research

Past studies of intra-stand species site index correlations in California have been fairly limited. Wensel and Krumland (1986) studied the relationship between north coastal Douglas-fir and redwood and found that Douglas-fir site indices were 10 to 20 feet higher when both species appeared in mixture. Wiant and Porter (1966) compared site indices of north coastal Douglas-fir, redwood, and associated hardwoods and made predictive models. Their study however utilized a variety of base ages (50 and 100 years), age bases (breast-high and total age), and some site index models that this study has found to be less suitable. Wensel (1997) provided ratio estimators for missing species site indices in interior mixed conifer stands. Powers (1972b) provided an equation to predict black oak site index from that of ponderosa pine.

7.2 Methods

Ideal data for species site index correlations require not only appropriate site index models for individual species but also unified site tree sample selection procedures. With the data at hand, the latter criterion is not always possible to achieve. The assumption was made that like site tree sampling rules in individual stands produce comparable proportions in species site index differences. Of several possible methods tried, the one outlined below produced the most consistent results.

1) Using what was considered to be the best site index model for the species/location, an average site index prediction was derived for each tree in the database based on all of the tree's height/age measurements.

2) The mean site index prediction of all trees of a given species in each stand and the standard error of the estimated mean was computed. Three trees of a given species were minimally required. These means were paired with the corresponding means of all other species that could be computed in the respective stand.

3) A model of the following general form was subsequently fit to the stand site index estimates:

$$S_y = a_0 + a_1 S_x \qquad [7.1]$$

where

S_y = Site index of species to be predicted

S_x = Estimated source species site index
a_0, a_1 = Linear regression coefficients to be estimated

4) Equation 7.1 is general and specific cases were sometimes reduced to restricted forms including:

   a) Mean predictions (a_1 =0). When overall regressions were insignificant, the mean value of S_y was used as the estimate of a_0 and a_1 was set to 0.

   b) When intercepts were not significantly different from 0, a_0 was set to 0 and only a_1 was estimated. This is essentially a least squares ratio estimator.

   c) In situations where both linear and least squares ratio estimates appear to give reasonable fits, both are given. In these situations, ratio estimates usually were quite close to results achieved by bivariate and orthogonal regressions or related techniques that attempt to split bivariate data centroids through their major axis.

5) Regression weights were initially taken to be inversely proportional to the sum of the squared standard errors of stand mean site index predictions of both the dependent and independent variable. This schema was adopted to give more weight to stand species pairs that contributed more individual trees to the stand average. However, it was found not to make any material difference in coefficient estimates so weights were not used.

6) Post analysis was undertaken to see if general relationships could be further refined by various physiographic conditions.

The estimation equations developed here are mainly from stands of natural origin and should only be used in these cases.

7.3 Results

Paired observations from over 2000 stands were initially available for analysis. However, sample sizes for many species combinations were insufficient to make meaningful comparisons. Table 7.1 shows coefficient estimates and a statistical synopsis by species for relationships that could reasonably be estimated. In general, precision of the estimates (R^2) is not great and standard deviations (RMSE) are in the 10-15 feet range.

7.3.1 North Coastal Species

Primary species in the Northern California Coast ecological section are redwood and Douglas-fir. Differences in site index between these species average about 13 percent but differences of up to 30 feet have been observed. Significant differences in north coastal intra-stand site index relationships due to topographical position, elevation, or counties were not apparent. The main redwood – Douglas-fir relationships shown in table 7.1 are consistent with the previous results of Wensel and Krumland (1986). The linear relationships are highly significant but give somewhat inconsistent inverse predictions in the tails of the respective species site index distributions. The ratio estimators are almost the same as those achieved by bi-variate regression. This is essentially an entirely different data view than linear regression approaches that answer the question of "what is Y given X"? The ratio estimators are much more inversely compatible. Compared to interior species, the precision (R^2) of redwood – Douglas-fir relationships is low. This is largely due to the inherent variability of redwood. Years of experience modeling redwood (tree volume, taper, DBH growth, etc.) indicate that residual variation is minimally twice as much as for associate species such as Douglas-fir.

Inverse linear relationships of redwood and Douglas-fir site indices are the most disparate of any species examined. Figure 7.1 shows data and linear relationships of redwood site index on that of Douglas-fir, Douglas-fir on that of redwood, and a ratio line which is about the same regardless of which species is the dependent variable. It is unknown whether these species differences are due to individual species population variability or totally different environmental preferences even though they frequently occupy the same physical sites. In any event, the relationship between Douglas-fir and redwood site index is weak. When site indices of both species are needed, they should both be measured in the field where possible. The low precision of correlations between these species warrants separate site index estimates when both species are abundant in a specific stand. While they are better than no information, the prediction equations from table 7.1 are not recommended for use on a routine basis for redwood or Northern California Coast Douglas-fir site index estimation.

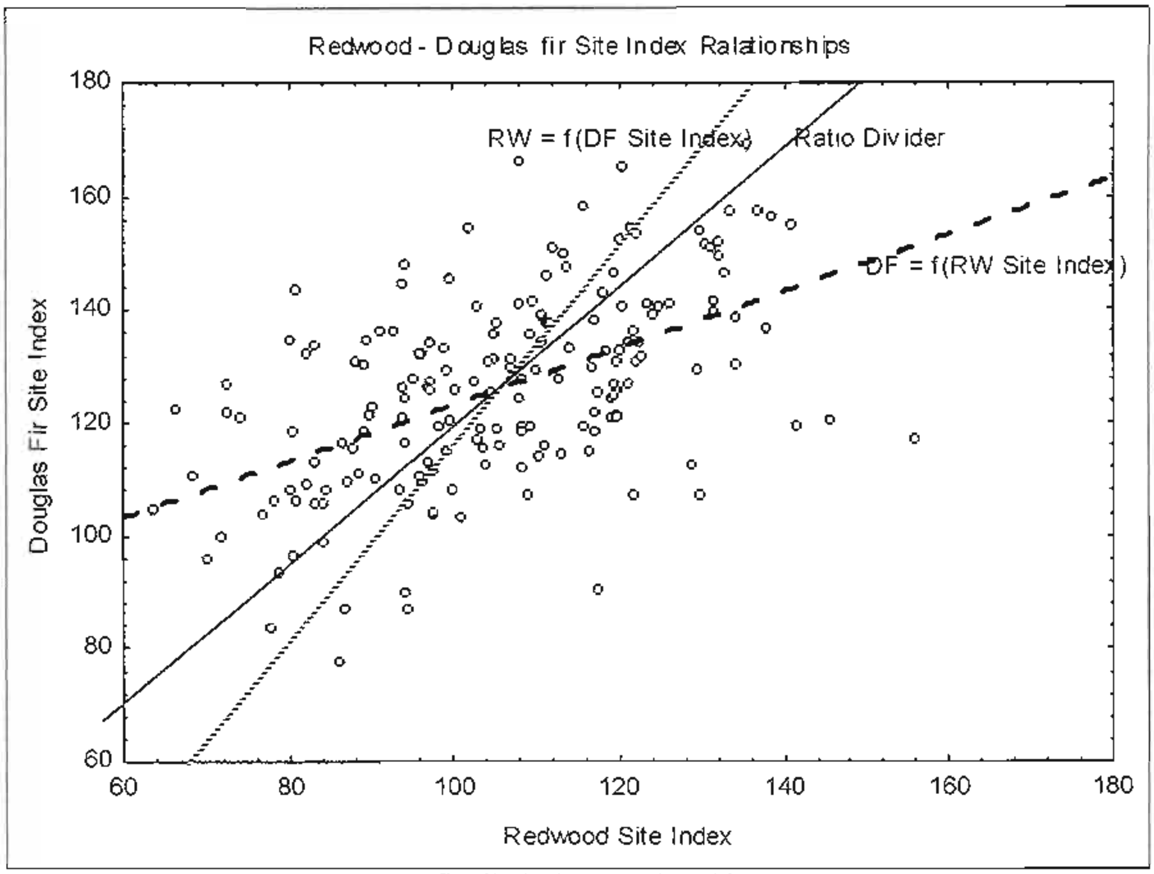

Figure 7.1. *Redwood – Douglas-fir site index relationships.*

Grand fir appears to always have the highest site index regardless of whether it is compared to redwood or Douglas-fir.

7.3.2 Interior Species

Table 7.1 indicates there is little evidence to suggest that the site indices of ponderosa pine, sugar pine, Douglas-fir, white fir and red fir, when growing in mixture, are materially different. Note that this is qualified for a 50-year breast-high age site index. Altering the base age to something other than 50 years will alter the MC3 species - true fir relationships. Numerous situations have been noticed where within stand site index differences between mixed conifer species approach almost a site class (20 feet). Some differences in intra-stand species site index relationships were found due to elevation and topographical position mainly between ponderosa pine/Douglas-fir and white fir. Site indices of the former tend to be slightly higher than white fir at lower elevations, particularly on southwest aspects. At higher elevations on northeast aspects, white fir site indices tended to be higher. However, given the resolution of the data, discrimination at this level of refinement was not considered to be justifiable.

Where situations warrant, species-specific site index estimates can be taken. The MC3 species site index models should be used for ponderosa pine, sugar pine and Douglas-fir in whichever zones they occur. Separate true fir site index models should be used for both white fir and red fir. Where one 'mixed conifer' site index is desired, sample selection procedures should be applied without regard to species. This will essentially weight species in proportion to their abundance.

Incense cedar site indices are uniformly about 35 percent less than associated species making incense cedar a poor choice as a component of a mixed conifer site classification system.

Table 7.1 Statistical summary of intra-stand species site index relationships.

Source Species (S_x)	Predicted Species (S_y)	Coefficients a_0	a_1	N	RMSE (ft.)	R^2
RW	DF	73.4	0.50	174	14.7	0.28
	DF		1.17	174	18.1	0.21
	GF		1.20	16	16.6	0.14
	TO	41.4	0.24	36	11.4	0.15
	MD	52		4		
	RA		0.71	11	10.8	0.24
DF (Northern California Coast)	RW	35.6	0.55	174	15.5	0.29
	RW		0.83	174	16.1	0.24
	GF		1.09	17	13.7	0.28
	TO	29.8	0.29	41	11.9	0.18
	MD	33.8	0.23	12	9.2	0.14
	RA	90		6		
PP	DFI	34.4	0.56	107	10.5	0.62
	DFI		0.98	107	11.3	0.58
	SP		0.98	78	11.5	0.75
	WF	26.5	0.73	149	13.5	0.59
	WF		1.05	149	15.4	0.53
	IC		0.65	68	10.4	0.53
	BO		0.52	28	8.9	0.46
DF (Interior)	PP		0.99	107	14.4	0.63
	SP		1.00	46	15.2	0.59
	WF		0.98	127	13.9	0.58
	IC		0.68	37	10.5	0.45
	BO		0.54	21	11.5	0.26
WF	PP		0.93	149	14.8	0.56
	SP		0.93	101	15.2	0.45
	DF		0.99	127	14.2	0.49
	RF		0.94	44	8.2	0.60
	IC		0.65	62	10.0	0.54
RF	WF		1.04	44	9.1	0.61
SP	PP		1.00	78	11.7	0.78
	WF		1.02	101	13.1	0.42
	DF		0.97	46	14.6	0.59
	IC		0.64	26	12.9	0.16

8. Site Tree Selection Protocol and Site Index Definitions

8.1 Site Tree Selection Protocol

This section provides a brief synopsis of the recommended site tree selection protocol. Further details can be found in following sections.

Characteristics of site trees should conform to the following:

1) No visual evidence of spiked tops, deformed tops, broken tops, or excessive defoliation. Trees should be relatively disease free. Basal logging or fire damage do not appear to have appreciable impacts on height growth development.

2) Crown ratios at the time of sampling should be at least 30 percent.

3) Trees should be minimally classed as either dominants or co-dominants, subject to specific selection rules.

4) Site trees should be over five inches in DBH and in the age range of 10 years to 100 years at breast height.

Sampling protocols that rely on proportionate numbers of the largest dominant and co-dominant trees by DBH are stable and can be applied in a systematic fashion. These rules do not rely on fine lines being drawn between dominant and co-dominant crown classes. The largest 20 percent or 40 percent of candidate site trees differ in resulting site index of an average of about two percent. The 40 percent rule is virtually the same as a random sample of dominant/co-dominant trees that are greater than the stand mean quadratic DBH. Any of these rules should provide a satisfactory site index sample basis.

The commonly used site tree sampling protocol of a random sample of dominant and co-dominant trees will usually result in trees having DBH greater than the stand quadratic mean DBH. In practice, this is probably the easiest method to implement and is therefore recommended. Site tree selection protocols that concentrate on selecting the "best" (tallest) site trees in the stand should be avoided.

8.1.1 Sample Size

Estimation of stand site index has two sources of error:

1) Within stand site index variability. This is the variation due to within stand site index estimates for the individual trees that make up the sample. This source of error can be controlled by the size of the sample.

2) Between stand site index variability. Site curves portray broad regional average trends in height growth development. Few stands however, will follow a site curve exactly. Thus, in specific stand site index applications, estimated site index will be biased by an unknown amount. This source of variability will decrease proportionately as trees approach the site index base age. There is nothing that

can be done to control this source of variability other than use the best site index models available.

Standard deviations of predicted site index will vary depending on a variety of factors. Representative ranges are shown in table 8.1 for common situations.

Table 8.1. Ranges in predicted site index standard deviation for common estimation situations.

Sampling conditions	**Prediction Standard Deviation (feet)**
Stem analysis measurements on single growth plots or closely spaced clusters in fairly homogenous stands.	5-10
Increment borings and standing tree height measurements on single growth plots or closely spaced clusters in fairly homogenous stands.	8 – 15
Increment borings and standing tree height measurements on operational areas of 20 to 40 acres.	12 –20+

What little data exist for analysis indicate that demarcated stands on slopes have topographical site index gradients. Site index tends to increase down slope.

Sample sizes can be computed by iteratively solving the following equation for n (Cochran, 1977):

$$n = \frac{S^2 t^2_{(\alpha,n)}}{H^2}$$

where

n = Number of site trees to sample.

t = Student's 't' value corresponding to probability level of $1-\alpha$ with n-1 degrees of freedom.

H = Desired half width of the confidence interval (feet).

S = Sample standard deviation.

Sample sizes are shown in table 8.2 for selected standard deviations, desired confidence intervals, and precision levels.

Table 8.2. Sample size requirements for desired confidence interval half widths by sample standard deviation and precision levels.

Confidence Interval Half Width (ft.)	Standard Deviation (ft.)	Precision Level (Probability %)		
		66%	90%	95%
5	5	3	5	6
	10	5	13	18
	15	10	26	37
	20	16	45	64
10	5	1	1	3
	10	3	5	6
	15	4	8	11
	20	5	13	18

8.2 Stand Site Index Definitions

Different definitions of stand site index and corresponding sampling rules for stand components can lead to different overall site index values. For example, definitions that involve co-dominant and dominant trees will in general produce lower site index values than definitions based solely on dominant trees. Similarly, definitions that are based on any form of superlatives will always be higher than average based measures. This section examines several definitions of stand site index and relates them to an arbitrary standard. Sampling efficiency of the various rules is also evaluated. This section does not consider possible bias due to individual stand departures from regional site index models (Type II polymorphism), but rather the variation and relative level of predicted stand site index based on site tree selection rules.

8.2.1 Stability of Tree Crown Class Classifications

Virtually all site tree-sampling rules involve selecting trees that are minimally classified as having a dominant or co-dominant crown classification. These are trees that are presumed to have grown free of height growth competition their entire lives. Classifying trees into crown classes however, is ultimately subjective. No objective standards currently exist. To provide some indication of the degree of stability of tree crown classifications, repeated tree crown class classifications from seven permanent plot data sets were examined. These data sets all had tree crown class as a standard measurement item. Definitions of tree crown class ranged from highly detailed descriptions with corresponding graphics to nothing. The following protocol was observed:

a) Only conifer trees were examined with no regard to species.
b) Two measurement sequences from each plot set were extracted, all with an interval between measurements of approximately 10 years.
c) Trees were 5.0 inches DBH and larger without any indication of spiked or broken tops or excessive defoliation.
d) Trees had to be alive on both occasions.

Plots were further subdivided into those that were harvested between measurements and those that were not. Harvested plots were those with at least one tree cut. This process produced about 53000 observed trees of which about 9000 were from harvested plots. Crown class movement ratios were subsequently computed and are shown in tables 8.3 and 8.4.

Table 8.3. Indicative crown class movement ratios for unharvested conifer stands.

Initial Crown Class	Proportion of trees by crown class 10 years later			
	Dominant	Co-Dominant	Intermediate	Suppressed
Dominant	.90	.10	--	--
Co-dominant	.14	.83	.03	--
Intermediate	.05	.34	.58	.03
Suppressed	.02	.14	.31	.53

Table 8.4. Indicative crown class movement ratios for harvested conifer stands.

Initial Crown Class	Proportion of trees by crown class 10 years later			
	Dominant	Co-Dominant	Intermediate	Suppressed
Dominant	.95	.05	--	--
Co-dominant	.19	.79	.02	--
Intermediate	.08	.38	.52	.02
Suppressed	.06	.22	.34	.38

Examination of tables 8.3 and 8.4 indicates that trees classified as either dominants or co-dominants tend to stay that way ten years later. There is a general tendency however, of upwards movement in all tree crown classes after logging. Successive classifications of intermediate and suppressed trees also tend to be highly variable. Movement ratios separated by source (data set) of trees are also highly variable. In some cases, groups of plots that can be traced to individual field crews show movement ratios into and out of dominant and co-dominant classes of over 35 percent. As a qualitative statement, it seems as though stability of tree crown classification is directly correlated to a) the amount of verbiage and diagrams that are included in field instructions, b) the amount of training field personnel go through in order to ensure consistency in crown classification and c) the amount of check cruising done to ensure standards are maintained.

8.2.2 Data

Data used to examine site index definitions came from growth or stem analysis data sets where virtually all of the trees were measured for breast-high age and total height at one measurement and had sufficient tree tally coding to ensure that potential site trees could be identified as being full crowned and damage free. The LDMC and LDRF stem analysis data sets had corresponding plot inventories that matched this criterion. The FIA data set was also used for this purpose with the 1990 measurement used as the representative inventory. Sample locations of all three data sets were organized into clusters of three to five plots each. Clusters were treated as stands in this analysis.

Qualifying Site Trees

Eligible site trees were minimally required to have the following characteristics:

1. Dominant or co-dominant crown class.
2. Crown ratios greater than or equal to 30 percent.
3. No visible signs of current or past leader damage such as forked tops, crooks, etc.
4. Tree breast-high ages in the range of 10 - 100 years.

Species Groups

Four species groups were examined and treated as composites for this analysis. Components and site index models used are shown in table 8.5.

Table 8.5. Species groups and site index models used in stand site index analysis.

Species Group	Component Species	Site Index Model
MC3	Ponderosa pine, sugar pine, interior Douglas-fir	MC3_CR2_MMC
TF	White fir, red fir	WF_CR2_Ca, RF_CR2_Ca
RW	Coast redwood	RW_KP1_NC
DF	North coast Douglas-fir	DF_KP1_NC

8.2.3 Stand Component

The following definitions were considered to span the range of possible choices of stand components for defining stand site index. Regardless of the definition, only qualifying site trees as defined above were considered in estimating site index. Stand components and rules are described in table 8.6.

Table 8.6 Stand component definitions used for defining stand site index.

Rule Name	Stand Component Definition
All DC	All dominant and co-dominant trees.
Dominants	All dominant trees.
Co-dominants	All co-dominant trees.
P20	Largest 20 percent by DBH of dominant and co-dominant trees.
P40	Largest 40 percent by DBH of dominant and co-dominant trees. Note: this rule produces results that are virtually identical to selecting all dominant and co-dominant trees with the added stipulation that they be larger than the mean stand quadratic mean DBH
D5	Largest dominant or co-dominant trees by DBH on each plot in a cluster. Tree DBH must be greater than the average stand quadratic mean DBH.
H5	Tallest dominant or co-dominant tree on each plot in a cluster.
D40	Equivalent largest 40 dominant or co-dominant trees per acre by DBH based on the entire cluster inventory.

Computations and Screening

Clusters that had more than 30 percent of the stand basal area in hardwoods were discarded. Otherwise, hardwoods were ignored in subsequent analysis. All trees less than 5.0 inches DBH were discarded. Trees were sorted largest to smallest by DBH regardless of species and the percentile in the stand DBH distribution and the numbers of trees per acre larger than the subject tree were recorded. For a sampling scheme to be considered for a species group, minimally three tally trees were required that matched the definition of eligible site index trees. Mean site index along with sample standard deviations and variances were subsequently computed for each species group and sampling scheme for each cluster.

From several hundred possible clusters, the numbers remaining that minimally satisfied the All DC definition are shown in table 8.7.

Table 8.7. Numbers of clusters by species group for site tree component analysis.

Species Group	Numbers of Clusters
DF	72
MC3	195
RW	91
TF	204

Differences Due to Stand Component Definitions

The *All DC* stand component definition was used as a standard basis for comparing and ranking other stand component definitions. Linear regressions of estimated stand site index from alternative stand component definitions on the *All DC* stand site index value for different species groups indicated the intercept terms were almost universally not significantly different from zero (p=.05). Also, results across data sources and species groups were surprisingly uniform. Thus, all sources and species groups were combined, regression estimators of the proportional difference from the *All DC* stand site index estimates were computed for each component definition and the results are shown in table 8.8.

Table 8.8 Proportional differences in stand site index rules from the All DC stand component.

Rule Name	Proportional Difference
H5	1.114
D5	1.073
Dominants	1.051
D40	1.047
P20	1.040
P40	1.021
Co-dominants	0.961

The H5, D5, and D40 sample selection rules in general produce higher relative site indices. Differences between these rules and the All DC basis however, were highly correlated with stand density expressed as trees per acre. The H5 selection rule for example, produces proportional differences of about 1.07 for stands with 100 trees per acre and values of about 1.14 for stands in the 300-400 trees per acre range. Also, the proportional differences presented here are contingent on the general plot layouts of the sample basis. Larger plots will in general inflate these values. For general stability in stand site index definitions, rules that rely on some absolute numbers of trees should be avoided. The Dominants, Co-dominants, P20, and P40 rules do not show significant trends in relative site index with trees per acre.

The Dominants, P20, and P40 rules are all fairly close in terms of providing the same relative site indices. In particular, the P20 and P40 rules only require that trees be classed as dominants or co-dominants and that one avoids drawing fine lines between upper canopy crown classes. King (1966) for example, found that a rule very similar to the P20 definition was stable and consistent for Douglas-fir trees in the Pacific Northwest.

Note that there is about a 10 percent differential between Dominant and Co-dominant trees in terms of relative site index. This is about one half of a site class on good sites.

8.2.4 Site Index Variability

Analysis of stand site index standard deviations (SSISD) for each site tree component definition indicated that there was more variability between data sources than component definitions. Figure 8.1 shows mean SSISD based on combined MC3 and TF species groups for each site tree component definition and data source (values would be about 0.75 feet higher if the square roots of pooled variances were used). The LDRF data set was a research plot series purposely placed in relatively homogenous young-growth red fir stand conditions. Numbers of countable inventory and qualifying site index trees averaged over twice those of the LDMC and FIA data sets. These factors were felt to contribute to generally lower mean SSISD values. Redwood and Douglas-fir, available only from the FIA data set showed similar site tree component definition patterns but all mean SSISD values were about 1.5 feet higher.

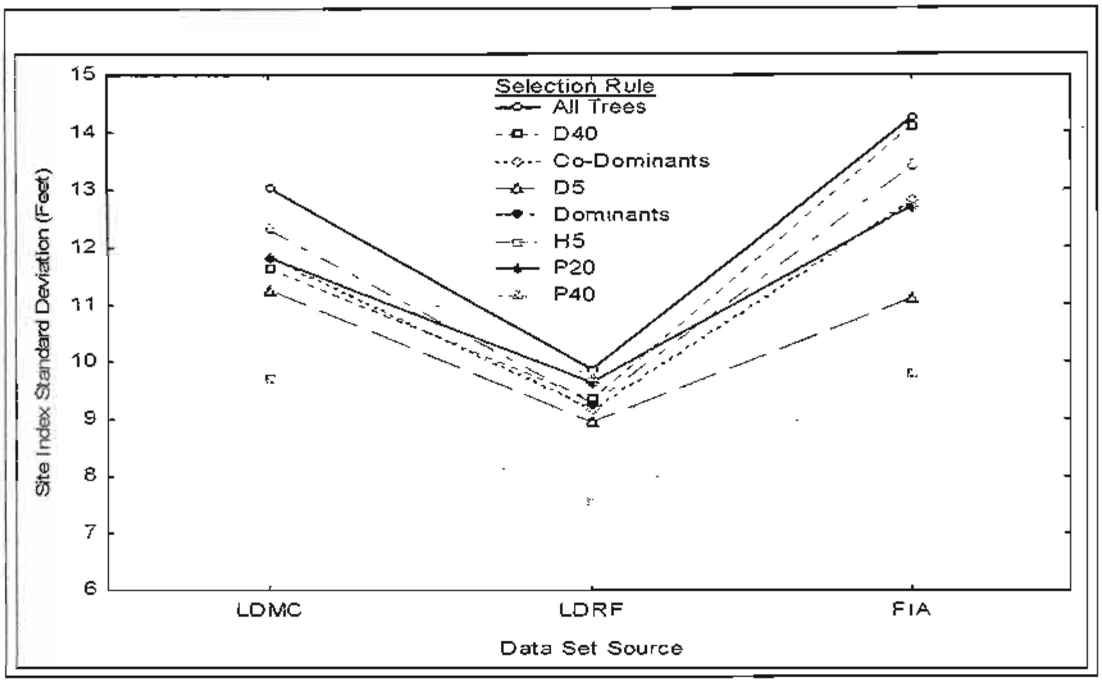

Figure 8.1. *Average within stand site index standard deviations by data source and site tree selection rule.*

Figure 8.1 indicates that the H5 and D5 site tree component rules are the most precise. As noted previously however, these rules (and D40) should be avoided due to consistency problems. The All DC rule is uniformly the least precise but it is not that much different from other rules.

Plots Versus Stands

A sub-analysis was undertaken where the site index sampling rules were applied to individual plots where possible (the H5, D5 or D40 rules were not considered) rather than aggregating values over all plots in each cluster. Overall rankings were similar to those shown for clusters in figure 8.1. Standard deviations of predicted values were in general about 2.5 feet lower making average SSISD values much more comparable to the plot based values reported by Krumland and Wensel (1977). This difference reflects within stand spatial variability of site index and suggests that trees that are closer together have relatively similar tree site indices. This difference reflects trees that have regenerated naturally as is the case with most of the sample. Differences in plantations are unknown at this point. The 2.5-foot difference reported here is nominal and reflects cluster layouts that effectively sampled areas of about 2 – 6 acres. Where site index is desired for larger operational treatment units or cover types, SSISD values will probably be greater than those shown in figure 8.1.

Stability of Stand Component Definitions

As an exploratory measure, standard deviations of SSISD values (this is a diagnostic rather than any form of a conventional statistic) were computed to provide a relative measure of the stability of site index sampling rules across stands. Pooled results for the MC3 and TF species groups are shown in table 8.9. The P20, P40, and All DC values rank the lowest and would appear to be the most stable.

Table 8.9 Standard deviations of estimated SSISD values for pooled MC3 and TF species groups by site index sampling scheme.

Rule Name	Standard Deviations (ft.)
Co-dominants	6.3
D5	6.2
Dominants	5.9
H5	5.2
D40	4.9
P20	4.7
All DC	4.6
P40	4.5

8.2.5 Discussion and Recommendations

Estimated stand site index, the average value of predicted tree heights at a base age, is in general an imprecise measure and can be influenced by the choice of site tree sample selection rules. The P20 or P40 rules appear to be the most precise and stable across different stands. The P40 produces site index values that are almost the same as the average site index of dominant and co-dominant trees whose DBH is greater than the stand quadratic mean diameter. All of these rules are replicable and fairly straightforward to implement in the field. The H5, D5 or any other rule that somehow concentrates on selecting the 'best' site trees should be avoided.

9. A Young Growth Conifer Site Class System

Currently, there are no consistent statewide site class systems for young growth stands in California based on a 50-year breast-high age site index. Existing old growth site class systems such as Dunning's (1942) are highly unstable when used to classify young growth mixed conifer stands. With the best collection of site index models available for various species and regions in the state and a large inventory of plots with estimated site indices, it is possible to examine the site class concept and propose a general 50-year breast-high age site class system that is suitable for the emerging young-growth resource.

9.1 Features of Site Class Systems

Site class[1], a range in site index values, is used for general forestry classification purposes, for regulatory compliance under the California forest practice rules, as a timberland taxation basis, and it is a common means for forestry professionals to refer to broad ranges in forest stand productivity. Desirable features of any site class system are:

a) The site classes should span the range of existing stand site indices.
b) Five to six site classes is in line with the common I through V and possibly I-A usage that currently exists in the State.
c) If site class I through V are used, then the middle of site class III should represent the average site index of the resource.
d) Site class site index breaks should be in multiples of easy to remember numbers (e.g. 5,10, 20).
e) Site class site index intervals should be equal so they can be remembered.
f) New systems should be as compatible as possible with existing systems.

Numerous site class systems have been proposed for use with different species in California. They span a range of breast-high/total ages and index ages of 50, 100, and 300 years. The common use of site class however, is much more ordinal in nature and could probably best be described as follows:

Site Class	Site Description
I-A	Very high
I	High
II	Good
III	Average
IV	Fair
V	Poor

[1] The word "site", as commonly used in forestry, will be considered synonymous with "site class" in this study.

9.2 Existing Site Class Systems

The existing site class systems that appear to be the origins of common site class usage in the State are Lindquist and Palley (1961) for redwood, McArdle and Meyer (1961) for north coastal Douglas-fir, and Dunning (1942) for interior mixed conifer forests. These site class systems are based on site curves with a variety of age bases and base (index) ages. They are all used as site class bases under the forest practice rules in the State of California. Using the 100-year site index break points specified in the forest practice rules, approximate site index break points were estimated for each system for a 50-year breast-high age base equivalent. These conversions are shown in table 9.1.

Table 9.1 Approximate 50-year breast-high age site index ranges for common site class systems in California. (Based on originating site index curves).

Site Class	Redwood	North coastal Douglas-fir	Mixed Conifer
	Site index range (feet)		
I	122 +	140 +	80+
II	102 – 122	120 –140	67 – 80
III	80 – 102	100 – 120	55 – 67
IV	60 – 80	80 - 100	42 – 55
V	<60	<80	< 42

The forest practice rules redwood site class system is based on 100-year breast-high ages with class intervals of 25 feet. Break points for the redwood site class system in the forest practice rules were apparently derived from the site index sampling distribution used to construct the site curves, as Lindquist and Palley loosely specified site classes of 20-foot intervals. This is not necessarily representative of the regional redwood site index distribution.

The forest practice rules site class system for north coastal Douglas-fir was based on 100-year total ages with 30-foot class intervals. Break points for the Douglas-fir site class system were apparently directly translated from the published site class bounds in McArdle and Meyer's study, which was based on Douglas-fir in Oregon and Washington. Following King (1966), 50-year breast-high age breaks were generated by adjusting total ages to breast-high ages by factors of six to 10 years for site classes I through V respectively and interpolating from the site tables.

The mixed conifer site class system is based on 300-year total ages with 25-foot class intervals. Three hundred year break points for the mixed conifer site class system were apparently directly translated from the published site class bounds in Dunning's study. Dunning's site curves were used in the State forest practice rules to adjust the 300-year break points to 100-year break points. Fifty-year breast-high age breaks were generated by adjusting total ages to breast-high ages by factors of six to 15 years for site classes 1 through V respectively and interpolating from the site tables.

There are two primary forested regions to address: the redwood – Douglas-fir region of the north coast and the interior mixed conifer forests. Data used in this phase consists of the sample data used in chapter 7: Intra-Stand Species Site Index Relationships.

9.3 Northern California Coast Forests

The first task is to describe the site index distribution of redwood and north coastal Douglas-fir. The FIA data set is based on a systematic sample of all lands that are not administered by the US Forest Service. There are no major US Forest Service holdings in the Northern California Coast ecological section, so we can assume this data source is representative of the site index distribution of both species. Because plot location in the FIA data set is confidential, only Douglas-fir stands that had evidence of redwood cohorts were initially considered. First, means and standard deviations of stand site index were computed for both species. As a check, similar statistics were computed for the JSF data set and three other industrial growth or CFI plot data sets that were systematically laid out over a combined area of more than 600,000 acres. Differences between these data partitions were minor. Mean redwood site index ranged from 98 to 105. Mean Douglas-fir site index ranged from 119 to 128. Standard deviations for both species in all data sets ranged from 18 to 23 feet. All species distributions, either in aggregate or individually appeared to be normal. Combining all data sources, empirical distributions are shown in figure 9.1.

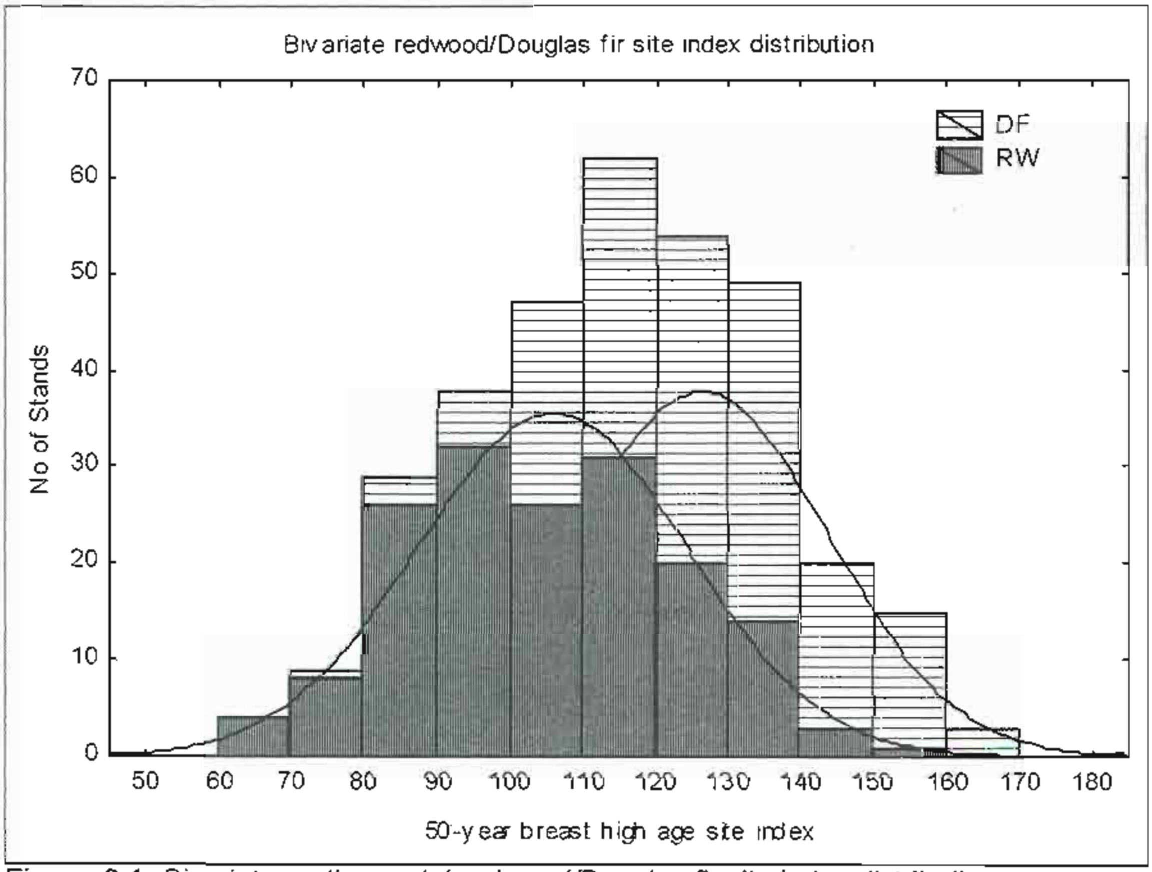

Figure 9.1. *Bivariate north coastal redwood/Douglas-fir site index distribution.*

As additional confirmation, the above procedure was repeated for both species individually. Overall redwood mean site index decreased from 103 to 101 feet. Douglas-fir mean site index decreased from about 126 feet to 117 feet. This decrease is primarily reflected in more stands in lower site index classes located in the eastern somewhat drier areas of the Northern California Coast ecological section.

9.3.1 North Coastal 50-year Breast-High Age Based Site Class System

The following conclusions are drawn from the above analysis:

a) Mean redwood site index is about 100,
b) Mean Douglas-fir site index is about 120,
c) 20 foot site index intervals seem appropriate to keep within the data range and the numbers of desirable site classes.

Given the existence of some rare but highly productive sites on the upper end that are not in the normal range of commercially operable sites but exist in the resource, site classes I-A through VI appear to fit the full range of site indexes. A proposed north coastal 50-year breast-high age base site class system is shown in table 9.2. The means of the data are centered to represent a site class III (the average site).

Table 9.2. Proposed 50-year breast-high age site classes for north coastal forests.

Site Class	Redwood	Douglas-fir
	Site index range (feet)	
I-A	150 +	170+
I	130 – 150	150 – 170
II	110 – 130	130 – 150
III	90 –110	110 – 130
IV	70 – 90	90 – 110
V	50 – 70	70 – 90
VI	<50	<70

9.3.2 Northern California Coast Evaluation and Comparisons

The site class breaks shown in table 9.2 conform to the desirable site class attributes previously listed. Consistent 20-foot intervals span the site index range of both species. The mean site index of both species is centered in the middle of site class III. Given that the within stand site index variation will be reflected in standard deviations in the 10-15 foot range, 20 foot intervals are wide enough so stands can be sampled for site index and classified without requiring large amounts of field samples. These quantitative boundaries correspond to widely accepted regional references to site quality. Relative to previously existing north coastal site class systems, this proposal keeps the same approximate 20-foot common site index interval but raises class boundaries by about 10 feet or half a site class.

9.4 Mixed Conifer Forests

Using the FIA data set to describe the site index distribution of interior mixed conifer lands is somewhat problematic as is it is based on a systematic sample of all lands not administered by the US Forest Service. US Forest Service land however, comprises over half of the interior commercial timberland. Industrial private land (about 25 percent of the statewide commercial forest ownership) is known in general to be of higher site quality than US Forest Service land. Similarly, while a considerable amount of plot data is available from both private and public lands, the samples were not systematically laid out over large areas and do not necessarily provide a representative cross section. However, this is all the data that is currently available.

As a first step, analysis from chapter 7 indicates that for a 50-year breast-high base age, site indexes of ponderosa pine, sugar pine, interior Douglas-fir, and true firs are comparable when growing as associates. Stand site indices were subsequently computed based on all qualifying species of this composite mixture. Three data sources were considered for site index distributional analysis: FIA, NCPlot, and LDMC. The NCplot data set covered an area of more than 1.5 million private industrial acres of mixed conifer land with the objective of gaining a good cross section of sites and growing conditions. The LDMC data set covered Forest Service mixed conifer lands on the west slope of the Sierra Nevada with similar objectives. Site index means, standard deviations, and sample sizes are shown in table 9.3.

Table 9.3. Mean mixed conifer site index and standard deviation by data source.

Data Source	Stands	Mean Site Index (feet)	Standard Deviation (feet)
FIA	298	66	19
NCPlot	603	73	19
LDMC	81	72	16

Distributions of all three data sources were approximately normal and the site index ranges were all about the same. The combined distribution from all three data sources is shown in figure 9.2.

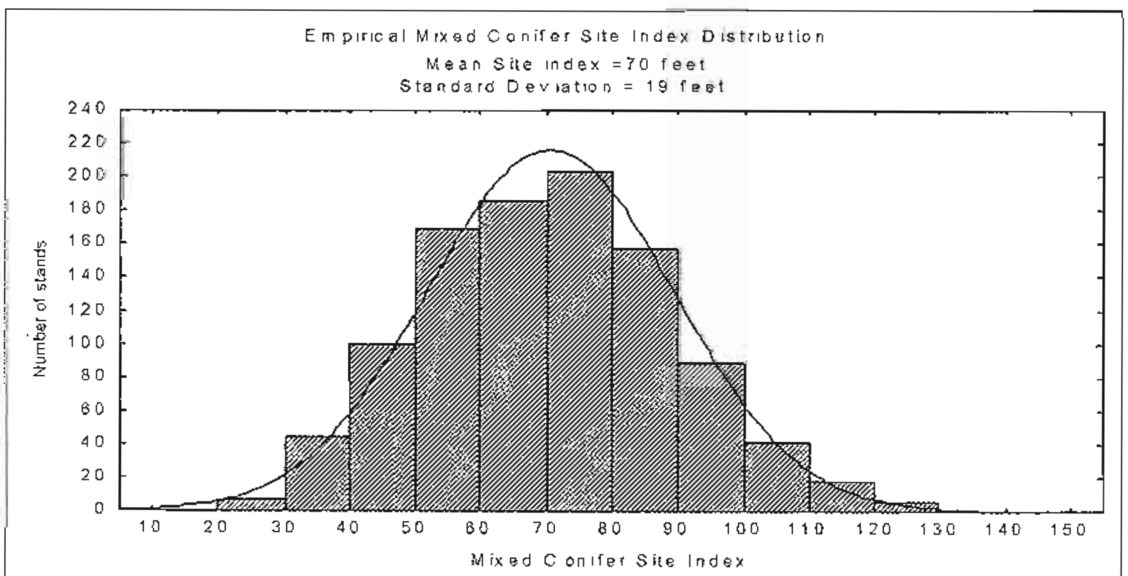

Figure 9.2 *Empirical mixed conifer site index distribution for California.*

9.4.1 Mixed Conifer 50-year Breast-High Age Based Site Class System

The above analysis indicates that an average mixed conifer site index of about 70 feet and a 20 foot site class interval are appropriate to keep within the data range and the desired number of site classes. Given the existence of some rare but highly productive sites on the upper end, site classes I-A through V adequately fit the whole range. Centering the means of the data to represent a site class III (the average site), an interior mixed conifer site class system is shown in table 9.4.

Table 9.4. Proposed 50-year breast-high age site classes for mixed conifer forests.

Site Class	Site Index Range (feet)
I-A	120 +
I	100 – 120
II	80 – 100
III	60 – 80
IV	40 – 60
V	<40

9.4.2 Mixed Conifer Comparisons and Evaluation

The site class breaks shown in table 9.4 conform to the desirable site class attributes previously listed. The site class system is centered to the estimated mean site index of the interior of the State. Consistent 20-foot intervals span the site index range. Communications with experienced foresters indicate that these site class breaks in general conform to the site class terminology currently used in the mixed conifer region.

The site class breaks bear little resemblance to Dunning's site classes. Dunning's site curves were developed specifically for old growth forests. Dunning recognized that his sample did not include the best sites. The best sites were primarily located on industrial private land where most of the old growth had been harvested at the time of his study. Dunning's site index intervals are in the 12-13 foot range when expressed on a 50-year basis. For a small tract of land, say 20 acres, a standard deviation in site index of about 15 feet would probably characterize the within stand site index variability. With this kind of variability, it would require about three times as many site trees to provide an estimate within 12-13 feet versus 20 feet at conventional levels of precision (90-95 percent probability). Dunning's translated 50-year intervals are a little narrow for practical use.

Using the *MC3_CR2_MMC* model as a reasonable representation of mixed conifer site tree development for California, Table 9.5 shows the corresponding Dunning's site class prediction at various ages for an average site index of 70.

Table 9.5. Dunning's site class based upon tree heights predicted with the MC3_CR2_MMC model for a site index of 70 feet.

Classification Age	Dunning's Site Class
10	V
20	IV
30	III
40	III
50	II
60	II
70	II
80	II
90	I

This table highlights the existence of pronounced bias in site class prediction with age. Dunning (1942) noted that his site curves were developed for estimating site index of old growth mixed conifers, and noted that when management focus shifted to young-growth, his curves may need to be abandoned.

9.5 Site Class Summary

The objective of this chapter was to propose young growth site class systems in line with the distribution of stand site index in different regions using what is considered to be the best site index models available. The latter ensures some independence of site classification with age.

Acceptance of any site class system requires general consensus and changes in regulatory statutes. The California forest practice rules contain explicit definitions of how to determine site index for various forms of regulatory compliance. Site class systems based on new site index models, regardless of the improvement, cannot be substituted without a change in regulatory statutes.

The 50-year breast-high age base site class proposal for the Northern California Coast redwood – Douglas-fir forests does little to change the current forest practice rules system other than provide site class breaks that are more compatible with how site index is currently estimated in the region. For the mixed conifer forests of the interior, the proposal is highly at odds with the current Dunning site classification system. The proposed site classification system is fairly stable across age classes. Dunning's old growth site classification can produce a wide range of values for the site class of a young-growth forest stand by selective choice of the age of the site trees.

The site class systems proposed here are in line with current regional usage of the term site class and provides quantitative site class breaks compatible with young growth site curves and 50-year base ages. Thus, for general consensus, little is changed by this young growth proposal.

In terms of timberland taxes, land site class classifications are already in place for all forested properties. Land values are based on transactions evidence or some other appraisal means relative to existing site classes. Consequently, if a new site class system is implemented it will not make much difference, yet the administrative burden would probably be prohibitive. Thus, current site class assignments in terms of property valuation for land taxes should probably not be altered.

10. Summary and Recommendations

GADA formulated base age invariant site index models have proven to be highly versatile in describing top height development of site trees. They provide generalizations of traditional height and site prediction models and can be used directly for both purposes. Coupled with unbiased estimation procedures, resulting models have been found to be the most accurate in describing the long-term growth trends of site trees.

10.1 Relationship to Existing Site Index Models

The site index models developed here or existing ones suggested for continued use appear to be the most accurate set of site index models currently available for major young-growth species in California. These models are recommended for future young-growth site index estimation and in general, predictions of top heights at any arbitrary age.

Substitution of these models for other curve families will depend on the anticipated use of site index. Growth models such as Systum-1, CRYPTOS, CACTOS, and the WESSIN FVS variant require site index to be estimated by specific existing site index models. Internal equations have been estimated using site index computed by these models as definitions. As a consequence, site index estimated by new models cannot easily be substituted. Strictly speaking, replacement of site index models requires all component growth equations to be re-estimated using new site index definitions. In general, any empirical relationship that utilizes site index as an independent variable (computed with a specific model and sampling rule) as an independent variable cannot have a new definition substituted without running the risk of corrupting the integrity of a model system. The BAI redwood and north coastal Douglas-fir site index models recommended here come quite close to the redwood (Wensel and Krumland, 1986) and Douglas-fir (King, 1966) site index models used in CRYPTOS. Simulation results indicate that using base age invariant site index estimates produces negligible differences in resulting stand growth predictions. With other models, the differences can be substantial, in which case substitution should be avoided.

10.2 Extensions

This study has made use of most of the historical height/age data and concomitant classification variables generally available for locations within the State. It has been both extensive in terms of breadth of species coverage and intensive in efforts to find broad-based physiographic factors that could be associated with different site curve family shapes. Attempts at the latter have only been marginally successful with three mixed conifer species: ponderosa pine, sugar pine, and interior Douglas-fir. It has become evident in the course of this study that site curve variation in the form of type II polymorphism is highly prevalent in the State, particularly in the interior. Common factors such as slope, aspect, elevation, and general location in the form of ecological sections have demonstrated some weak correlations in explaining variability. The approach in this study was largely empirical. It is apparent that process-based approaches accounting for climate, location features and soil properties offer the greatest opportunities for increasing the accuracy of site-specific site index applications.

Precision gains in terms of increasingly stand specific site curve shapes can proceed in several directions, none of which are mutually exclusive:

A. Individual site curve families can be constructed for specific tracts, or watersheds. While traditional approaches required complete stem analysis of trees old enough to span a site index base age, it has been demonstrated here that reasonable base age invariant site curves can be constructed with minimally two height/age pairs per tree as the common denominator. Such measurements can be obtained from a) repeated growth plot measurements, b) temporary borings in conjunction with whorl measurements where possible, and c) partial stem analysis collected in conjunction with logging operations. Growth period length should be carefully evaluated to ensure that there are no undue short term fluctuations that are at odds with longer overall growth trends.

B. Regional site curves can be constructed that are more specific than say, the broad based zonal MC3 models developed here. The most likely candidate variables to include would appear to be soil properties. Soil depth is probably the most likely factor to account for substantial amounts of type II polymorphism. Digital databases and publicly available GIS soils layers however are not yet universally available for all areas in the State. In the meantime, field collection of site index related data in whatever form should routinely be expanded to include GPS locations of sampling sites. Historically, field sampling locations have traditionally been recorded to the nearest quarter or sixteenth section ('40'). This is insufficient to accurately locate soil polygons.

10.3 Extended Availability

All of the base age invariant site index models developed in this study have been packaged as ActiveX™ components so they can be incorporated in spreadsheets, database programs, and application software compatible with 32-bit versions of the Microsoft Windows™ operating system. These software components and a demonstration program that can produce graphs and tables as found in Appendix I and throughout this report and also interactively estimate site index from measured heights and ages, are available from the California Department of Forestry and Fire Protection, State Forests Program: http://www.fire.ca.gov.

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Appendix I: Site Index Graphs, Tables, and Distribution Maps

I.1 Introduction

This appendix contains site index graphs and tables for the major base age invariant site index models developed in the course of this study. Not all models are shown. The companion site index program (see Section 10.3 for availability) however, can be used to produce a complete set of tables and graphs for all of the site index models developed here as well several historic studies.

To provide a visualization of the extent of the data and how well height development corresponds with site index models, the empirical time series data used in fitting the respective models are shown as overlays on site curve graphs for conifer species fit with the IE method. Data points of models fit with the HMC method are shown in graphics presented in Chapter 6.

Geographical distributions of sampling locations (stands) of major conifers fit to models employing the IE method are also provided. Due to incomplete locational data, sampling locations of hardwood and minor conifers are limited to the number of sampling locations (stands) by county.

I.2 Conifer Site Index Models

I.2.1 Redwood

Model Name: RW_KP1_NC
Model Form: KP1

Synopsis

The redwood site index model RW_KP1_NC is applicable to redwood in the north coast redwood region of California. The data used in fitting the site index model was confined to the redwood zone in Humboldt, Del Norte, and Mendocino counties. The approximate breast-high age range of the data 10 – 100 years and the site index range is 60 - 140 feet.

The RW_KP1_NC model is not much different than the alternative RW_CR1_NC model or the previous model of Wensel and Krumland (1986).

Figure I.1 shows the time series data used in fitting the model. Figure I.2 shows site curve graphs. Table I.1 provides tabular values of heights by breast-high age and site index. Figure I.3 maps the redwood sampling locations.

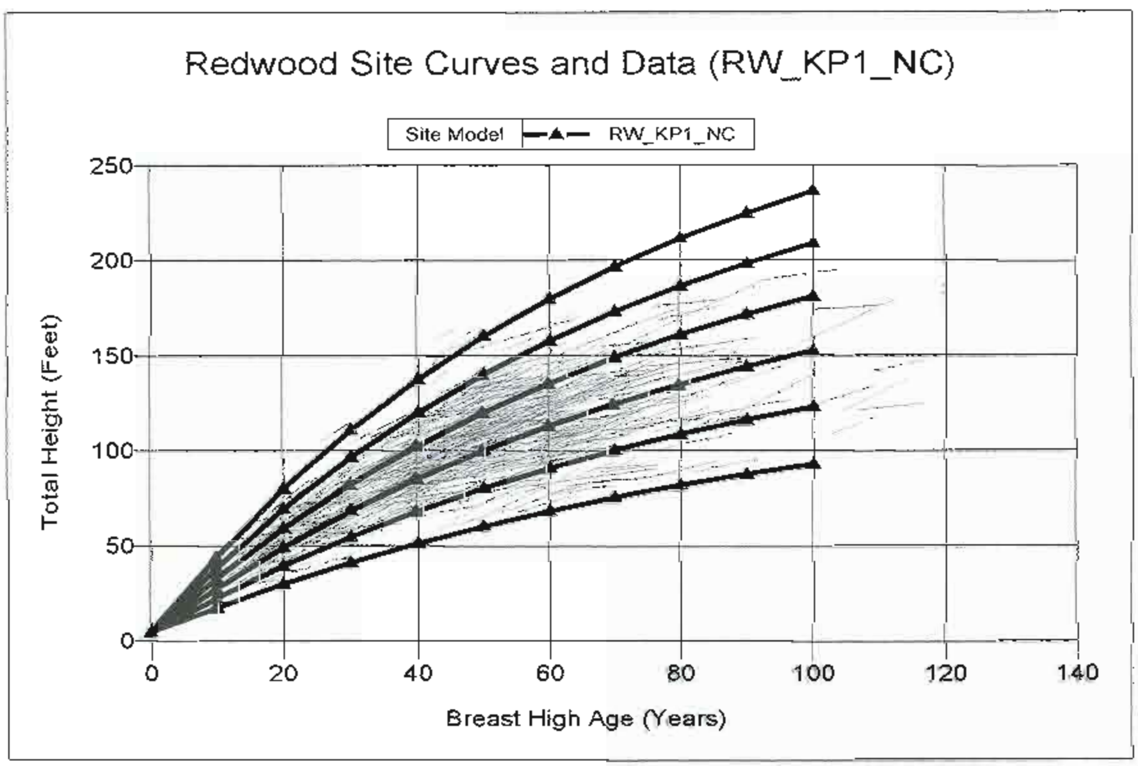

Figure I.1 Redwood data used in site model construction.

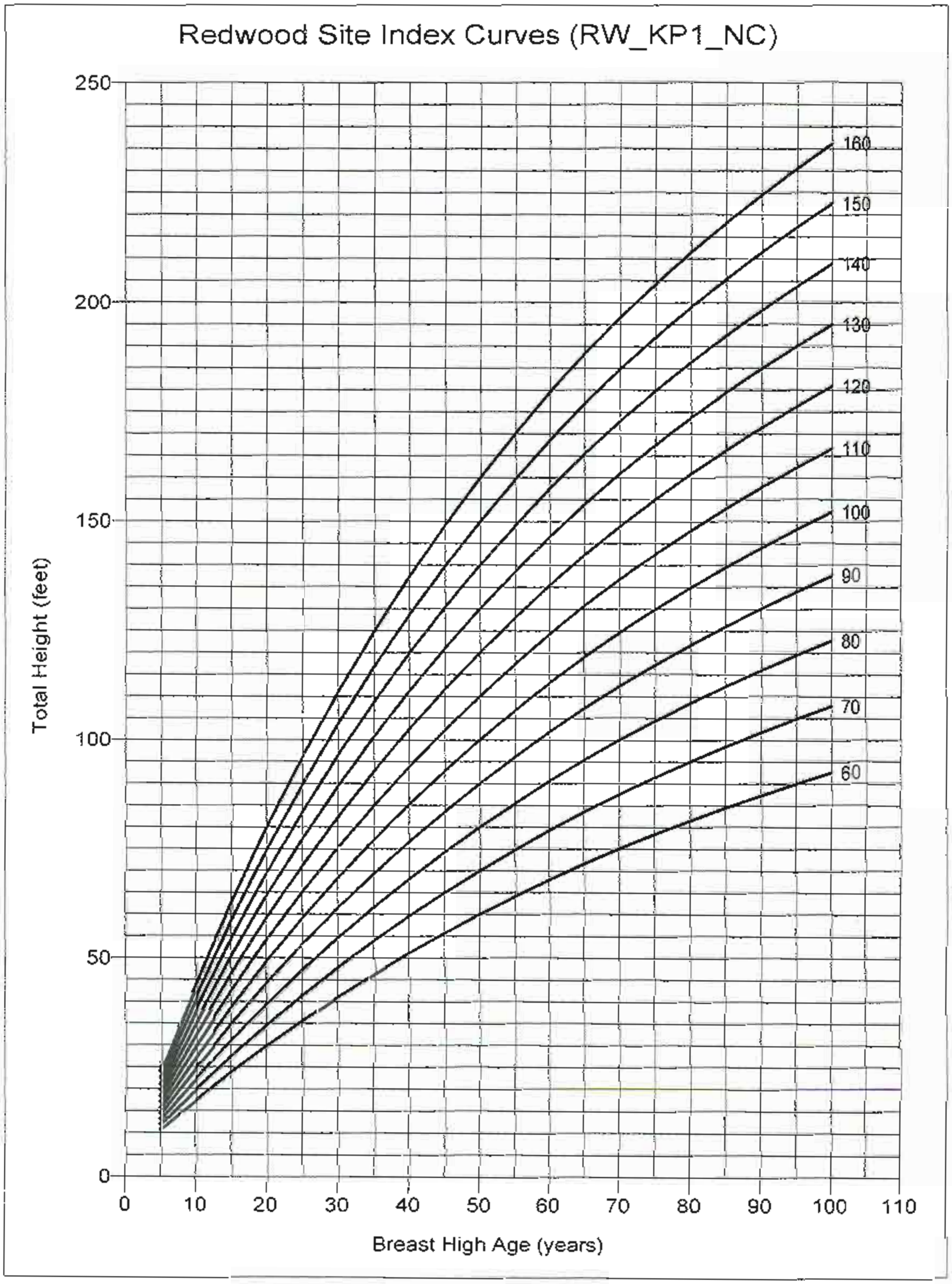

Figure I.2. *Redwood site index curves for the RW_KP1_NC model.*

Table I.1. Redwood site index table for the model RW_KP1_NC.

Redwood Site Index Table (RW_KP1_NC)

Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index																				
Age	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160
12	19.9	21.3	22.8	24.3	25.8	27.3	28.8	30.3	31.9	33.4	35.0	36.6	38.1	39.8	41.4	43.0	44.7	46.3	48.0	49.7	51.4
14	22.4	24.1	25.8	27.5	29.3	31.0	32.8	34.5	36.3	38.1	39.9	41.7	43.6	45.4	47.3	49.2	51.1	53.0	54.9	56.9	58.8
16	24.9	26.8	28.8	30.7	32.7	34.7	36.6	38.6	40.7	42.7	44.7	46.8	48.9	51.0	53.1	55.2	57.3	59.5	61.7	63.8	66.0
18	27.4	29.5	31.7	33.8	36.0	38.2	40.4	42.7	44.9	47.2	49.4	51.7	54.0	56.4	58.7	61.1	63.4	65.8	68.2	70.6	73.1
20	29.8	32.1	34.5	36.9	39.3	41.7	44.1	46.6	49.1	51.5	54.0	56.5	59.1	61.6	64.2	66.7	69.3	71.9	74.6	77.2	79.9
22	32.1	34.7	37.3	39.9	42.5	45.1	47.8	50.4	53.1	55.8	58.5	61.2	64.0	66.7	69.5	72.3	75.1	77.9	80.7	83.6	86.5
24	34.4	37.2	40.0	42.8	45.6	48.5	51.3	54.2	57.1	60.0	62.9	65.8	68.7	71.7	74.7	77.7	80.7	83.7	86.7	89.8	92.9
26	36.7	39.6	42.6	45.6	48.7	51.7	54.8	57.8	60.9	64.0	67.1	70.2	73.4	76.5	79.7	82.9	86.1	89.3	92.5	95.8	99.0
28	38.9	42.0	45.2	48.4	51.6	54.9	58.1	61.4	64.7	67.9	71.2	74.6	77.9	81.2	84.6	88.0	91.3	94.7	98.2	101.6	105.0
30	41.0	44.4	47.8	51.2	54.6	58.0	61.4	64.8	68.3	71.8	75.3	78.8	82.3	85.8	89.3	92.9	96.5	100.0	103.6	107.2	110.9
32	43.1	46.7	50.2	53.8	57.4	61.0	64.6	68.2	71.9	75.5	79.2	82.8	86.5	90.2	93.9	97.7	101.4	105.2	108.9	112.7	116.5
34	45.2	48.9	52.6	56.4	60.2	63.9	67.7	71.5	75.3	79.1	83.0	86.8	90.7	94.5	98.4	102.3	106.2	110.1	114.1	118.0	121.9
36	47.2	51.1	55.0	58.9	62.9	66.8	70.8	74.7	78.7	82.7	86.7	90.7	94.7	98.7	102.8	106.8	110.9	115.0	119.0	123.1	127.2
38	49.1	53.2	57.3	61.4	65.5	69.6	73.7	77.8	82.0	86.1	90.3	94.5	98.6	102.8	107.0	111.2	115.4	119.6	123.9	128.1	132.3
40	51.1	55.3	59.5	63.8	68.1	72.3	76.6	80.9	85.2	89.5	93.8	98.1	102.4	106.8	111.1	115.5	119.8	124.2	128.5	132.9	137.3
42	52.9	57.3	61.7	66.1	70.6	75.0	79.4	83.9	88.3	92.8	97.2	101.7	106.1	110.6	115.1	119.6	124.1	128.6	133.1	137.6	142.1
44	54.8	59.3	63.9	68.4	73.0	77.6	82.2	86.8	91.3	95.9	100.5	105.1	109.8	114.4	119.0	123.6	128.2	132.9	137.5	142.2	146.8
46	56.5	61.3	66.0	70.7	75.4	80.1	84.8	89.6	94.3	99.0	103.8	108.5	113.3	118.0	122.8	127.5	132.3	137.0	141.8	146.6	151.3
48	58.3	63.1	68.0	72.9	77.7	82.6	87.5	92.3	97.2	102.1	106.9	111.8	116.7	121.6	126.4	131.3	136.2	141.1	146.0	150.8	155.7
50	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0	125.0	130.0	135.0	140.0	145.0	150.0	155.0	160.0
52	61.7	66.8	71.9	77.1	82.2	87.4	92.5	97.6	102.7	107.9	113.0	118.1	123.2	128.4	133.5	138.6	143.7	148.8	153.9	159.0	164.1
54	63.3	68.6	73.9	79.1	84.4	89.6	94.9	100.2	105.4	110.7	115.9	121.2	126.4	131.6	136.9	142.1	147.3	152.5	157.7	163.0	168.2
56	64.9	70.3	75.7	81.1	86.5	91.9	97.3	102.7	108.0	113.4	118.8	124.1	129.5	134.8	140.1	145.5	150.8	156.1	161.5	166.8	172.1
58	66.5	72.0	77.5	83.1	88.6	94.1	99.6	105.1	110.6	116.0	121.5	127.0	132.4	137.9	143.3	148.8	154.2	159.6	165.1	170.5	175.9
60	68.0	73.7	79.3	85.0	90.6	96.2	101.8	107.4	113.0	118.6	124.2	129.8	135.4	140.9	146.5	152.0	157.5	163.1	168.6	174.1	179.6
62	69.5	75.3	81.0	86.8	92.6	98.3	104.0	109.8	115.5	121.2	126.9	132.5	138.2	143.9	149.5	155.1	160.8	166.4	172.0	177.6	183.2
64	70.9	76.8	82.7	88.6	94.5	100.3	106.2	112.0	117.8	123.6	129.4	135.2	141.0	146.7	152.5	158.2	163.9	169.6	175.3	181.0	186.7
66	72.4	78.4	84.4	90.4	93.4	102.3	108.3	114.2	120.1	126.0	131.9	137.8	143.7	149.5	155.4	161.2	167.0	172.8	178.5	184.3	190.1
68	73.8	79.9	86.0	92.1	98.2	104.3	110.3	116.4	122.4	128.4	134.4	140.4	146.3	152.2	158.2	164.1	170.0	175.8	181.7	187.5	193.4
70	75.1	81.4	87.6	93.8	100.0	106.2	112.3	118.5	124.6	130.7	136.8	142.8	148.9	154.9	160.9	166.9	172.9	178.8	184.8	190.7	196.6
72	76.5	82.8	89.2	95.5	101.8	108.0	114.3	120.5	126.7	132.9	139.1	145.3	151.4	157.5	163.6	169.7	175.7	181.7	187.8	193.8	199.7
74	77.8	84.3	90.7	97.1	103.5	109.9	116.2	122.5	128.8	135.1	141.4	147.6	153.8	160.0	166.2	172.3	178.5	184.6	190.7	196.7	202.8
76	79.1	85.6	92.2	98.7	105.2	111.6	118.1	124.5	130.9	137.3	143.6	149.9	156.2	162.5	168.7	175.0	181.2	187.4	193.5	199.6	205.8
78	80.3	87.0	93.6	100.2	106.8	113.4	119.9	126.4	132.9	139.4	145.8	152.2	158.6	164.9	171.2	177.5	183.8	190.1	196.3	202.5	208.7
80	81.6	88.3	95.1	101.8	108.4	115.1	121.7	128.3	134.9	141.4	147.9	154.4	160.8	167.3	173.7	180.0	186.4	192.7	199.0	205.2	211.5
82	82.8	89.6	96.5	103.3	110.0	116.8	123.5	130.1	136.8	143.4	150.0	156.5	163.1	169.6	176.0	182.5	188.9	195.3	201.6	207.9	214.2
84	84.0	90.9	97.8	104.7	111.6	118.4	125.2	131.9	138.7	145.3	152.0	158.6	165.2	171.8	178.3	184.8	191.3	197.8	204.2	210.6	216.9
86	85.1	92.2	99.2	106.1	113.1	120.0	126.8	133.7	140.5	147.3	154.0	160.7	167.4	174.0	180.6	187.2	193.7	200.2	206.7	213.1	219.6
88	86.3	93.4	100.5	107.5	114.6	121.5	128.5	135.4	142.3	149.1	155.9	162.7	169.4	176.1	182.8	189.4	196.0	202.6	209.1	215.6	222.1
90	87.4	94.6	101.8	108.9	116.0	123.1	130.1	137.1	144.0	150.9	157.8	164.7	171.5	178.2	185.0	191.7	198.3	204.9	211.5	218.1	224.6
92	88.5	95.8	103.0	110.2	117.4	124.6	131.7	138.7	145.8	152.7	159.7	166.6	173.4	180.3	187.1	193.8	200.5	207.2	213.9	220.5	227.0
94	89.5	96.9	104.3	111.6	118.8	126.0	133.2	140.3	147.4	154.5	161.5	168.5	175.4	182.3	189.1	195.9	202.7	209.5	216.1	222.8	229.4
96	90.6	98.1	105.5	112.9	120.2	127.5	134.7	141.9	149.1	156.2	163.3	170.3	177.3	184.2	191.1	198.0	204.8	211.6	218.4	225.1	231.8
98	91.6	99.2	106.7	114.1	121.5	128.9	136.2	143.5	150.7	157.9	165.0	172.1	179.1	186.2	193.1	200.0	206.9	213.8	220.6	227.3	234.0
100	92.6	100.2	107.8	115.4	122.8	130.3	137.6	145.0	152.3	159.5	166.7	173.9	181.0	188.0	195.0	202.0	209.0	215.8	222.7	229.5	236.2

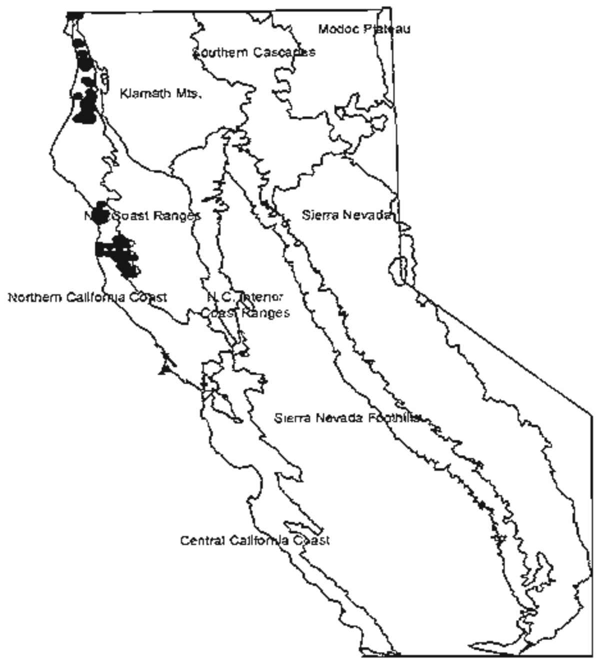

Figure I.3. *Redwood Sampling Locations in California.*

I.2.2 Coastal Douglas-fir

Model Name: DF_KP1_Ca
Model Form: KP1

Synopsis

The coastal Douglas-fir site index model DF_KP1_NC is applicable to Douglas-fir in the North Coast region of California. The data used in fitting the site index model was confined to the redwood zone in Humboldt, Del Norte, and Mendocino counties. The approximate breast-high age range of the data 10 – 80 years and the site index range is 70 - 170 feet.

The DF_KP1_NC model is very similar to the alternative DF_SH1_NC model and the model developed by King(1966) for Douglas-fir in the Pacific Northwest. The DF_KP1_NC model can also be used for interior Douglas-fir forest types, except in the main mixed conifer zone. This region is largely in the Northern California Coast range and Klamath Mtns. ecological sections. In the 40-100 site index range, this model is virtually the same as the MC3_CR2_OMC site curves.

Figure I.4 shows the time series data used in fitting the model. Figure I.5 shows site curve graphs. Table I.2 provides tabular values of heights by breast-high age and site index. Figure I.6 maps the Douglas-fir sampling locations.

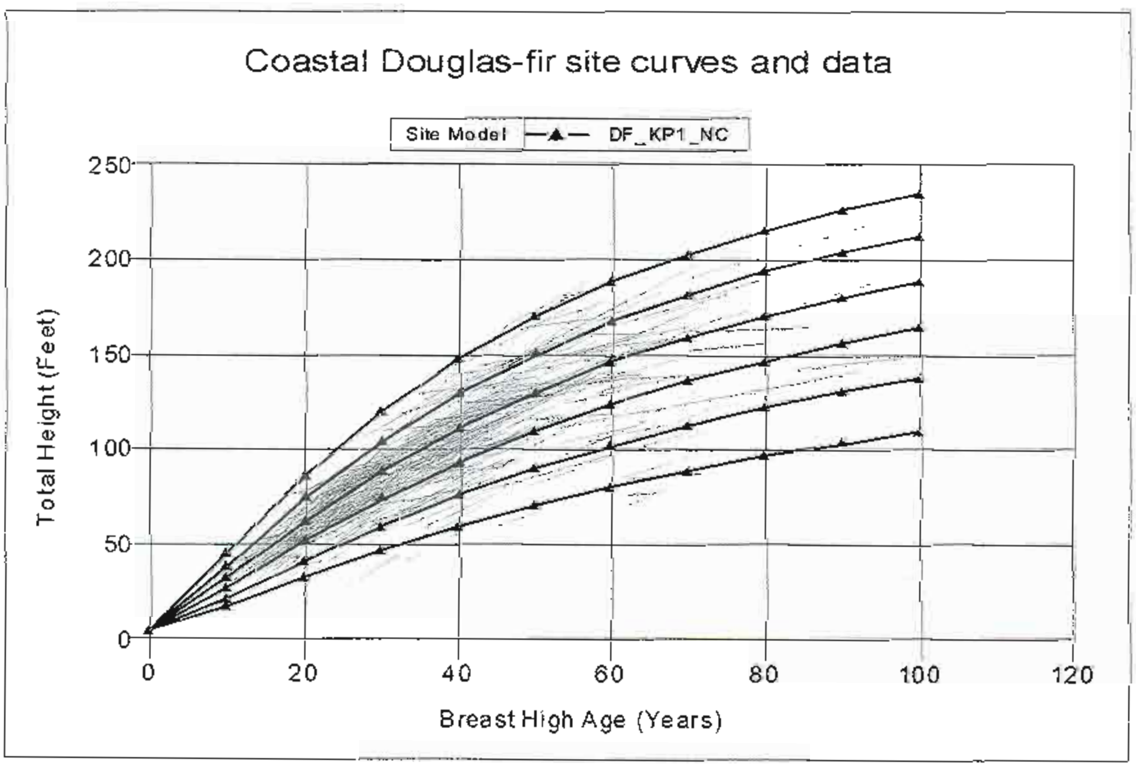

Figure I.4. *Coastal Douglas-fir site index data used in model construction.*

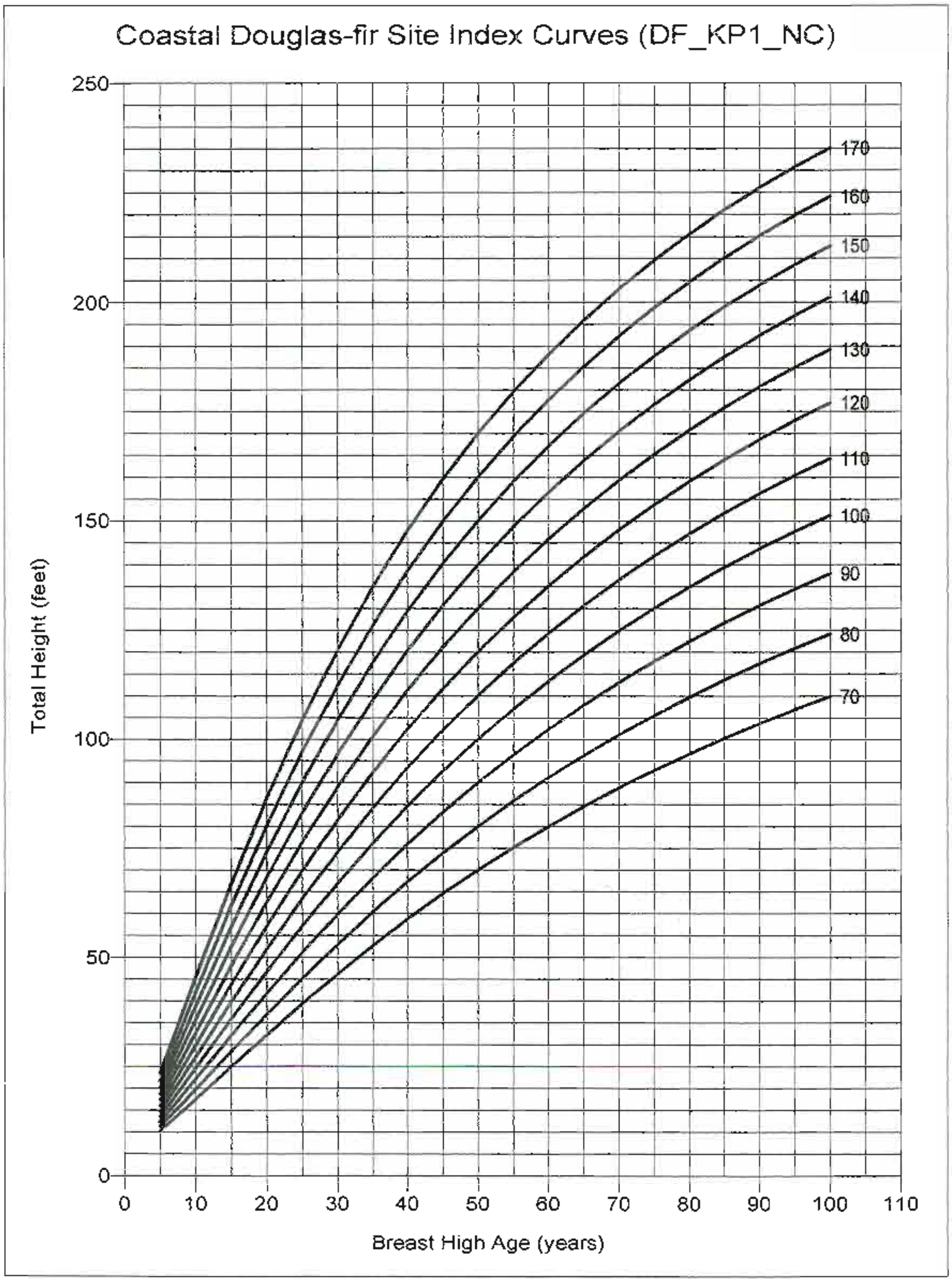

Figure I.5. *Coastal Douglas fir site index curves for the DF_KP1_NC model.*

Table I.2. Coastal Douglas fir site index table for the DF_KP1_NC model.

Coastal Douglas-fir Site Index Table (DF_KP1_NC)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index																
Age	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
12	12.6	13.9	15.1	16.4	17.7	19.0	20.4	21.8	23.2	24.6	26.1	27.6	29.1	30.6	32.2	33.8	35.5
14	14.2	15.7	17.1	18.7	20.2	21.8	23.4	25.0	26.6	28.3	30.0	31.8	33.6	35.4	37.2	39.1	41.1
16	15.8	17.5	19.2	20.9	22.7	24.5	26.3	28.2	30.1	32.0	34.0	36.0	38.0	40.1	42.2	44.4	46.5
18	17.3	19.2	21.2	23.2	25.2	27.2	29.3	31.4	33.5	35.7	37.9	40.1	42.4	44.7	47.1	49.5	51.9
20	18.9	21.0	23.2	25.4	27.6	29.9	32.2	34.5	36.9	39.3	41.7	44.2	46.7	49.3	51.9	54.5	57.2
22	20.4	22.8	25.2	27.6	30.1	32.5	35.1	37.6	40.2	42.8	45.5	48.2	51.0	53.7	56.6	59.4	62.3
24	22.0	24.5	27.1	29.8	32.5	35.2	37.9	40.7	43.5	46.3	49.2	52.1	55.1	58.1	61.1	64.2	67.3
26	23.5	26.3	29.1	31.9	34.8	37.7	40.7	43.7	46.7	49.8	52.8	56.0	59.1	62.3	65.6	68.8	72.2
28	25.0	28.0	31.0	34.1	37.2	40.3	43.4	46.6	49.8	53.1	56.4	59.7	63.1	66.5	69.9	73.4	76.9
30	26.5	29.7	32.9	36.2	39.4	42.8	46.1	49.5	52.9	56.4	59.9	63.4	66.9	70.5	74.1	77.8	81.5
32	27.9	31.3	34.7	38.2	41.7	45.2	48.8	52.3	55.9	59.6	63.2	66.9	70.7	74.4	78.2	82.0	85.9
34	29.3	32.9	36.6	40.2	43.9	47.6	51.3	55.1	58.9	62.7	66.5	70.4	74.3	78.2	82.2	86.2	90.2
36	30.8	34.6	38.4	42.2	46.1	50.0	53.9	57.8	61.8	65.7	69.8	73.8	77.8	81.9	86.0	90.2	94.4
38	32.2	36.1	40.1	44.1	48.2	52.2	56.3	60.4	64.6	68.7	72.9	77.1	81.3	85.5	89.8	94.1	98.4
40	33.5	37.7	41.9	46.1	50.3	54.5	58.7	63.0	67.3	71.6	75.9	80.3	84.6	89.0	93.4	97.8	102.3
42	34.9	39.2	43.6	47.9	52.3	56.7	61.1	65.5	70.0	74.4	78.9	83.4	87.9	92.4	96.9	101.5	106.1
44	36.2	40.7	45.2	49.7	54.3	58.8	63.4	68.0	72.6	77.2	81.8	86.4	91.1	95.7	100.4	105.0	109.7
46	37.5	42.2	46.8	51.5	56.2	60.9	65.7	70.4	75.1	79.9	84.6	89.4	94.1	98.9	103.7	108.5	113.3
48	38.8	43.6	48.4	53.3	58.1	63.0	67.9	72.7	77.6	82.5	87.3	92.2	97.1	102.0	106.9	111.8	116.7
50	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0
52	41.2	46.4	51.5	56.7	61.8	67.0	72.1	77.2	82.4	87.5	92.6	97.7	102.8	107.9	113.0	118.1	123.2
54	42.4	47.7	53.0	58.3	63.6	68.9	74.1	79.4	84.6	89.9	95.1	100.3	105.5	110.8	116.0	121.1	126.3
56	43.6	49.1	54.5	59.9	65.3	70.7	76.1	81.5	86.9	92.2	97.6	102.9	108.2	113.5	118.8	124.1	129.3
58	44.8	50.4	55.9	61.5	67.0	72.6	78.1	83.6	89.0	94.5	99.9	105.4	110.8	116.2	121.5	126.9	132.2
60	45.9	51.6	57.3	63.0	68.7	74.4	80.0	85.6	91.2	96.7	102.3	107.8	113.3	118.8	124.2	129.7	135.1
62	47.0	52.9	58.7	64.5	70.3	76.1	81.8	87.5	93.2	98.9	104.5	110.1	115.7	121.3	126.8	132.3	137.8
64	48.1	54.1	60.1	66.0	71.9	77.8	83.6	89.5	95.2	101.0	106.7	112.4	118.1	123.7	129.3	134.9	140.5
66	49.2	55.3	61.4	67.4	73.5	79.5	85.4	91.3	97.2	103.1	108.9	114.6	120.4	126.1	131.8	137.4	143.0
68	50.2	56.5	62.7	68.9	75.0	81.1	87.1	93.1	99.1	105.1	111.0	116.8	122.6	128.4	134.2	139.9	145.5
70	51.2	57.6	63.9	70.2	76.5	82.7	88.8	94.9	101.0	107.0	113.0	118.9	124.8	130.7	136.5	142.2	148.0
72	52.2	58.7	65.2	71.6	77.9	84.2	90.5	96.7	102.8	108.9	115.0	121.0	126.9	132.8	138.7	144.5	150.3
74	53.2	59.8	66.4	72.9	79.3	85.7	92.1	98.3	104.6	110.8	116.9	123.0	129.0	135.0	140.9	146.8	152.6
76	54.2	60.9	67.6	74.2	80.7	87.2	93.6	100.0	106.3	112.6	118.8	124.9	131.0	137.0	143.0	148.9	154.8
78	55.1	62.0	68.7	75.4	82.1	88.7	95.2	101.6	108.0	114.3	120.6	126.8	132.9	139.0	145.1	151.0	156.9
80	56.0	63.0	69.9	76.7	83.4	90.1	96.7	103.2	109.6	116.0	122.4	128.6	134.8	141.0	147.1	153.1	159.0
82	57.0	64.0	71.0	77.9	84.7	91.4	98.1	104.7	111.2	117.7	124.1	130.4	136.7	142.9	149.0	155.1	161.1
84	57.8	65.0	72.1	79.1	86.0	92.8	99.5	106.2	112.8	119.3	125.8	132.2	138.5	144.7	150.9	157.0	163.0
86	58.7	66.0	73.1	80.2	87.2	94.1	100.9	107.7	114.3	120.9	127.4	133.9	140.2	146.5	152.7	158.9	164.9
88	59.6	66.9	74.2	81.3	88.4	95.4	102.3	109.1	115.8	122.5	129.0	135.5	141.9	148.3	154.5	160.7	166.8
90	60.4	67.9	75.2	82.4	89.6	96.7	103.6	110.5	117.3	124.0	130.6	137.1	143.6	150.0	156.3	162.5	168.6
92	61.2	68.8	76.2	83.5	90.8	97.9	104.9	111.9	118.7	125.5	132.1	138.7	145.2	151.6	158.0	164.2	170.4
94	62.0	69.7	77.2	84.6	91.9	99.1	106.2	113.2	120.1	126.9	133.6	140.3	146.8	153.3	159.6	165.9	172.1
96	62.8	70.5	78.1	85.6	93.0	100.3	107.4	114.5	121.5	128.3	135.1	141.8	148.3	154.8	161.2	167.5	173.8
98	63.6	71.4	79.1	86.6	94.1	101.4	108.7	115.8	122.8	129.7	136.5	143.2	149.8	156.4	162.8	169.1	175.4
100	64.4	72.3	80.0	87.6	95.2	102.6	109.8	117.0	124.1	131.0	137.9	144.7	151.3	157.9	164.3	170.7	177.0

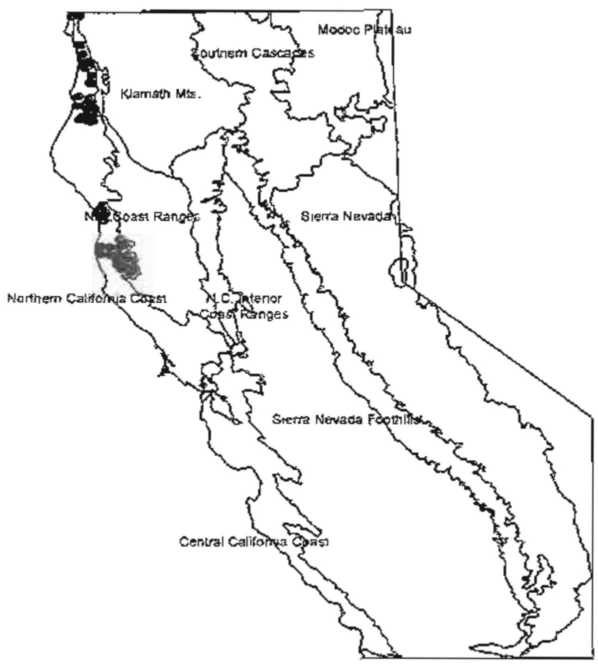

Figure I.6. *Coastal Douglas-fir sampling locations in California.*

I.2.3 Grand fir

Model Name: GR_CR1_NC
Model Form: CR1

Synopsis

The grand fir site index model GF_CR1_NC is applicable to grand fir in the Northern California Coast ecological section. The data used in fitting the site index model was confined primarily to the redwood zone in Humboldt, Del Norte, and Mendocino counties. The approximate breast-high age range of the data is 10 – 65 years and the site index range is 115 - 155 feet.

Data used to construct the grand fir site index index was relatively sparse but clearly shows a distinction from Douglas-fir in terms of height growth development

Figure I.7 shows the time series data used in fitting the model. Figure I.8 shows site curve graphs. Table I.3 provides tabular values of heights by breast-high age and site index. Figure I.9 maps the grand fir sampling locations.

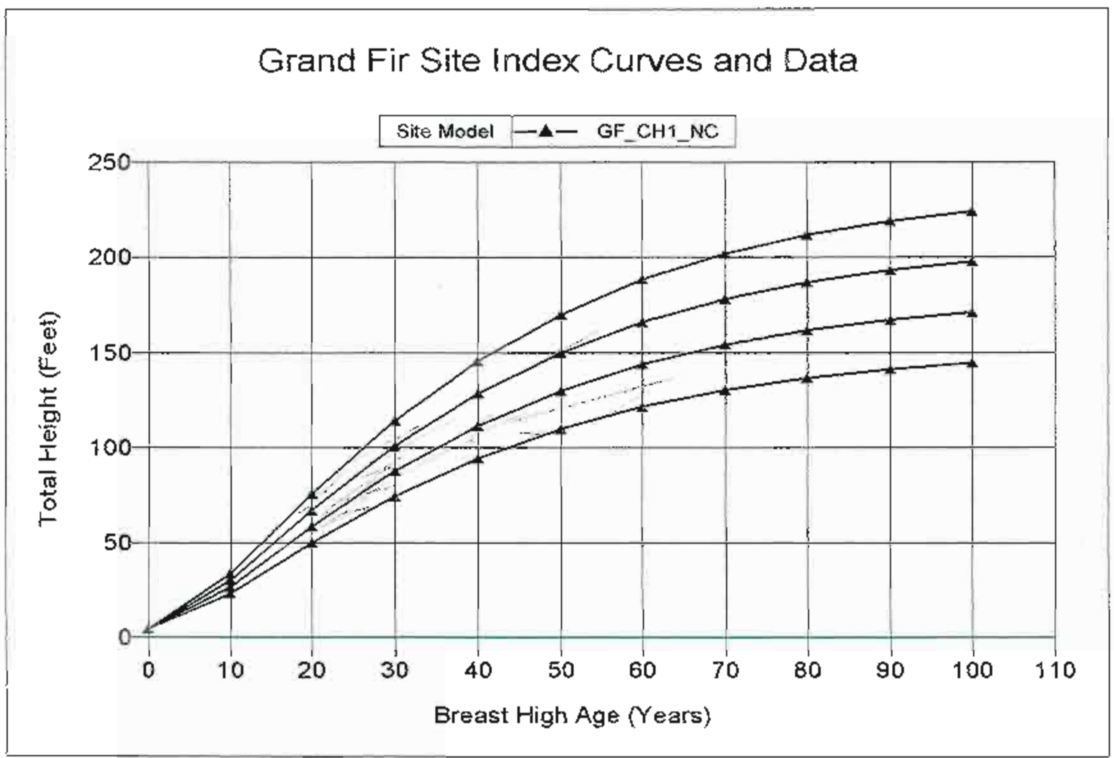

Figure I.7. *Grand fir height growth data used in model construction.*

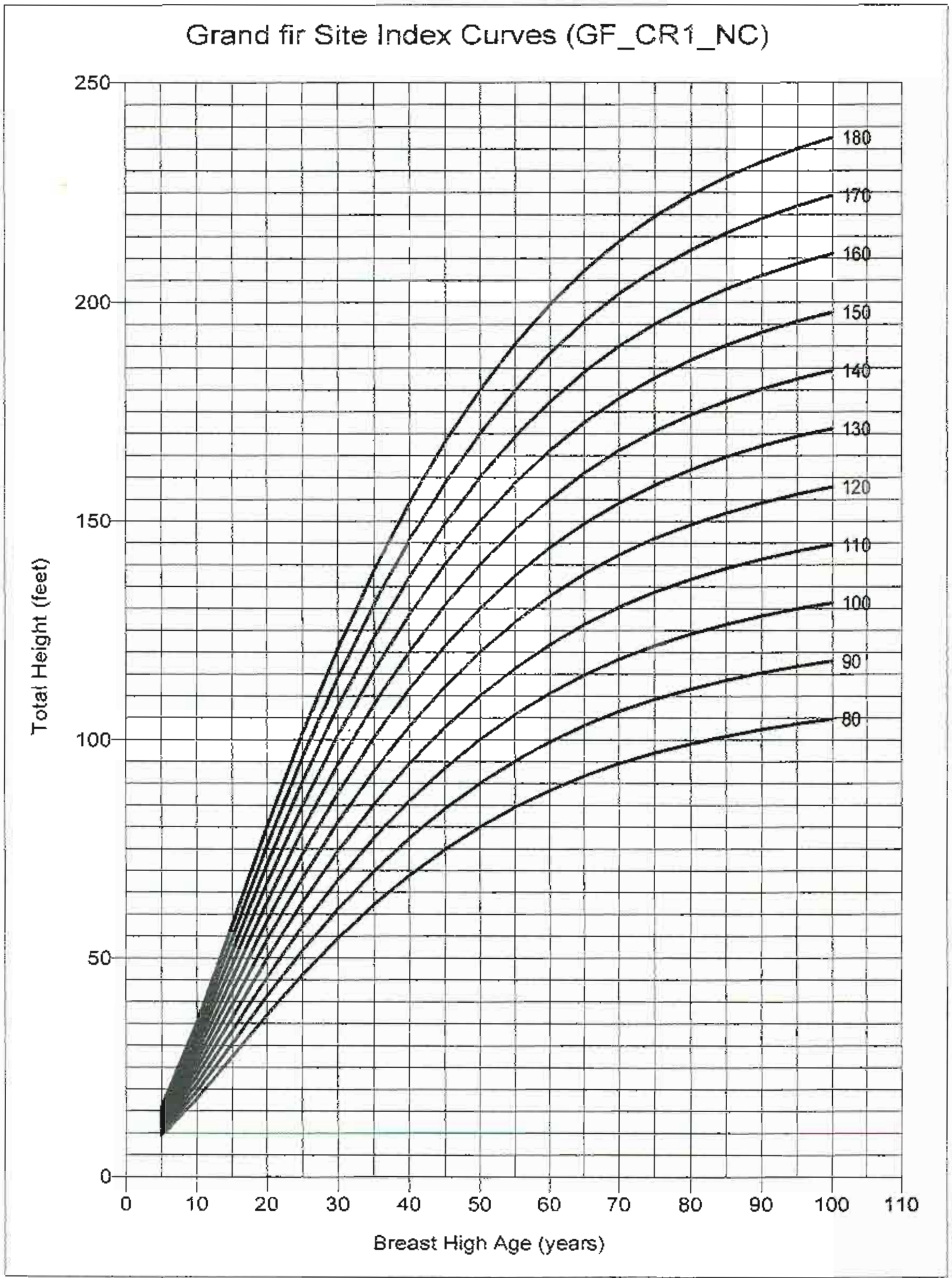

Figure I.8 *Grand fir site index curves for the GR_CR1_NC model.*

Table I.3 Grand fir site index table for the GR_CR1_NC model.

Grand Fir Site Index Table (GR_CR1_NC)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index														
Age	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170
12	26.1	27.2	28.3	29.5	30.6	31.7	32.8	34.0	35.1	36.2	37.4	38.5	39.6	40.8	41.9
14	31.0	32.3	33.7	35.1	36.5	37.9	39.3	40.6	42.0	43.4	44.8	46.2	47.6	49.0	50.3
16	35.9	37.5	39.2	40.8	42.4	44.1	45.7	47.4	49.0	50.6	52.3	53.9	55.6	57.2	58.9
18	40.8	42.7	44.6	46.5	48.4	50.2	52.1	54.0	55.9	57.8	59.7	61.6	63.5	65.4	67.3
20	45.6	47.7	49.9	52.0	54.2	56.3	58.5	60.6	62.8	64.9	67.1	69.2	71.4	73.5	75.7
22	50.3	52.7	55.1	57.5	59.9	62.3	64.7	67.1	69.5	71.9	74.3	76.7	79.1	81.5	83.9
24	54.9	57.5	60.2	62.8	65.5	68.1	70.7	73.4	76.0	78.7	81.3	83.9	86.6	89.2	91.9
26	59.4	62.2	65.1	68.0	70.9	73.7	76.6	79.5	82.3	85.2	88.1	91.0	93.8	96.7	99.6
28	63.7	66.8	69.9	73.0	76.1	79.2	82.3	85.4	88.4	91.5	94.6	97.7	100.8	103.9	107.0
30	67.8	71.1	74.4	77.8	81.1	84.4	87.7	91.0	94.3	97.6	101.0	104.3	107.6	110.9	114.2
32	71.8	75.3	78.8	82.3	85.9	89.4	92.9	96.4	100.0	103.5	107.0	110.5	114.0	117.6	121.1
34	75.6	79.3	83.0	86.7	90.5	94.2	97.9	101.6	105.3	109.1	112.8	116.5	120.2	124.0	127.7
36	79.2	83.1	87.0	90.9	94.8	98.8	102.7	106.6	110.5	114.4	118.3	122.2	126.1	130.0	134.0
38	82.7	86.8	90.8	94.9	99.0	103.1	107.2	111.3	115.4	119.5	123.6	127.7	131.8	135.9	139.9
40	85.9	90.2	94.5	98.7	103.0	107.3	111.5	115.8	120.1	124.3	128.6	132.9	137.1	141.4	145.6
42	89.1	93.5	97.9	102.4	106.8	111.2	115.6	120.1	124.5	128.9	133.3	137.8	142.2	146.6	151.1
44	92.0	96.6	101.2	105.8	110.4	114.9	119.5	124.1	128.7	133.3	137.9	142.4	147.0	151.6	156.2
46	94.8	99.6	104.3	109.0	113.8	118.5	123.2	127.9	132.7	137.4	142.1	146.9	151.6	156.3	161.0
48	97.5	102.4	107.2	112.1	117.0	121.8	126.7	131.6	136.4	141.3	146.2	151.0	155.9	160.8	165.6
50	100.0	105.0	110.0	115.0	120.0	125.0	130.0	135.0	140.0	145.0	150.0	155.0	160.0	165.0	170.0
52	102.4	107.5	112.6	117.7	122.9	128.0	133.1	138.2	143.4	148.5	153.6	158.7	163.9	169.0	174.1
54	104.6	109.9	115.1	120.3	125.6	130.8	136.1	141.3	146.5	151.8	157.0	162.3	167.5	172.7	178.0
56	106.7	112.1	117.4	122.8	128.1	133.5	138.8	144.2	149.5	154.9	160.2	165.6	170.9	176.3	181.6
58	108.7	114.2	119.6	125.1	130.5	136.0	141.4	146.9	152.4	157.8	163.3	168.7	174.2	179.6	185.1
60	110.6	116.1	121.7	127.2	132.8	138.4	143.9	149.5	155.0	160.6	166.1	171.7	177.2	182.8	188.3
62	112.3	118.0	123.6	129.3	134.9	140.6	146.2	151.9	157.5	163.2	168.8	174.5	180.1	185.8	191.4
64	114.0	119.7	125.5	131.2	136.9	142.7	148.4	154.1	159.9	165.6	171.3	177.1	182.8	188.5	194.3
66	115.6	121.4	127.2	133.0	138.8	144.6	150.5	156.3	162.1	167.9	173.7	179.5	185.4	191.2	197.0
68	117.0	122.9	128.8	134.7	140.6	146.5	152.4	158.3	164.2	170.1	176.0	181.8	187.7	193.6	199.5
70	118.4	124.4	130.3	136.3	142.3	148.2	154.2	160.2	166.1	172.1	178.1	184.0	190.0	196.0	201.9
72	119.7	125.7	131.8	137.8	143.8	149.9	155.9	161.9	168.0	174.0	180.0	186.1	192.1	198.1	204.2
74	120.9	127.0	133.1	139.2	145.3	151.4	157.5	163.6	169.7	175.8	181.9	188.0	194.1	200.2	206.3
76	122.1	128.2	134.4	140.5	146.7	152.9	159.0	165.2	171.3	177.5	183.6	189.8	195.9	202.1	208.3
78	123.1	129.4	135.6	141.8	148.0	154.2	160.4	166.6	172.8	179.1	185.3	191.5	197.7	203.9	210.1
80	124.2	130.4	136.7	142.9	149.2	155.5	161.7	168.0	174.3	180.5	186.8	193.1	199.3	205.6	211.9
82	125.1	131.4	137.7	144.0	150.4	156.7	163.0	169.3	175.6	181.9	188.2	194.5	200.9	207.2	213.5
84	126.0	132.3	138.7	145.1	151.4	157.8	164.1	170.5	176.9	183.2	189.6	195.9	202.3	208.7	215.0
86	126.8	133.2	139.6	146.0	152.4	158.8	165.2	171.6	178.0	184.4	190.8	197.3	203.7	210.1	216.5
88	127.6	134.0	140.5	146.9	153.4	159.8	166.3	172.7	179.1	185.6	192.0	198.5	204.9	211.4	217.8
90	128.3	134.8	141.3	147.8	154.3	160.7	167.2	173.7	180.2	186.7	193.1	199.6	206.1	212.6	219.1
92	129.0	135.5	142.0	148.6	155.1	161.6	168.1	174.6	181.2	187.7	194.2	200.7	207.2	213.7	220.3
94	129.6	136.2	142.7	149.3	155.9	162.4	169.0	175.5	182.1	188.6	195.2	201.7	208.3	214.8	221.4
96	130.2	136.8	143.4	150.0	156.6	163.2	169.7	176.3	182.9	189.5	196.1	202.7	209.2	215.8	222.4
98	130.8	137.4	144.0	150.6	157.3	163.9	170.5	177.1	183.7	190.3	196.9	203.5	210.2	216.8	223.4
100	131.3	138.0	144.6	151.3	157.9	164.5	171.2	177.8	184.5	191.1	197.7	204.4	211.0	217.7	224.3

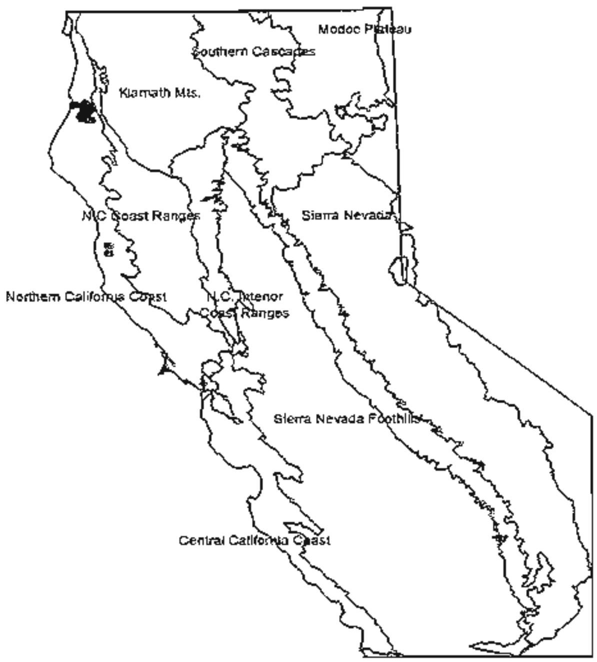

Figure I.9. *Grand fir sampling locations in California.*

I.2.4 MC3 Species – Main Mixed-Conifer Zone

Model Name: MC3_CR2_MMC
Model Form: CR2

Synopsis

The MC3_CR2_MMC site index model is applicable to MC3 species (ponderosa pine, interior Douglas-fir, and sugar pine) in the main mixed conifer zone. This zone roughly encompasses mixed-conifer site in the 3000-6000 elevation band on the west slope of the Sierra Nevada's and the Southern Cascades and comparable sites in the Klamath mountains. (cf Section 6.2.2 for more details). The age range is approximately 10 to 100 years and the site index range is 40 – 120 feet.

Individual MC3 species-specific models were also developed but they are not appreciably different from the MC3_CR2_MMC model.

Figure I.10 shows the time series data used in fitting the model. Figure I.11 shows site curve graphs. Table I.4 provides tabular values of heights by breast-high age and site index. Figure I.12 maps the MC3 species sampling locations in the main mixed conifer zone.

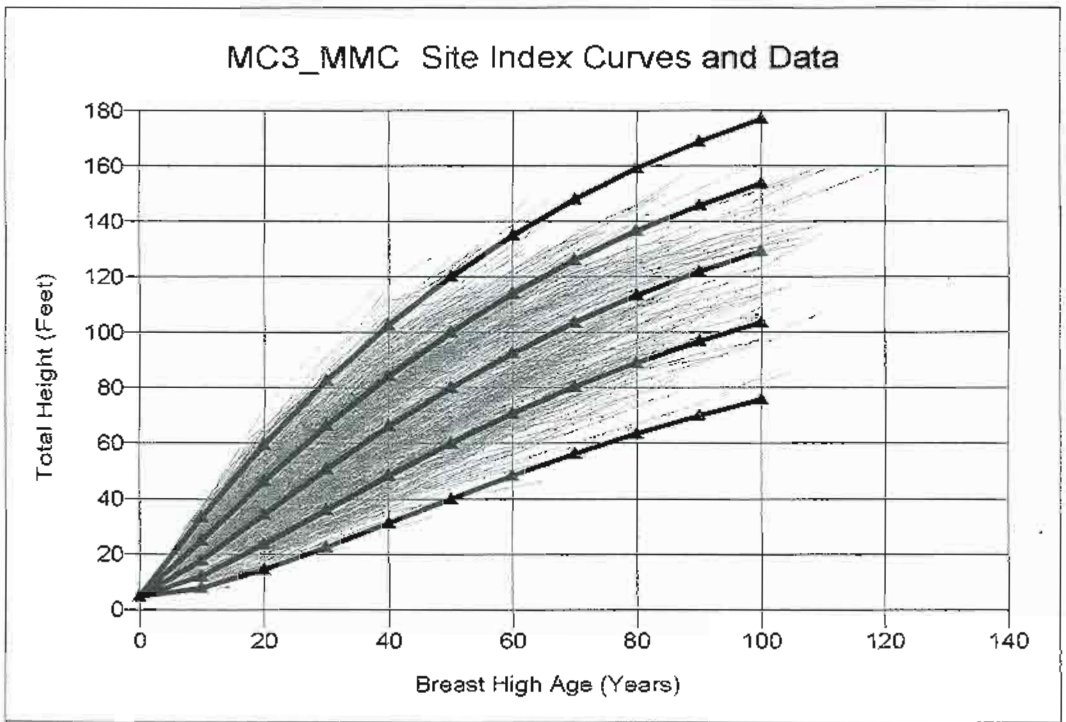

Figure 1.10. MC3 species height growth data used in model construction for the main mixed conifer zone.

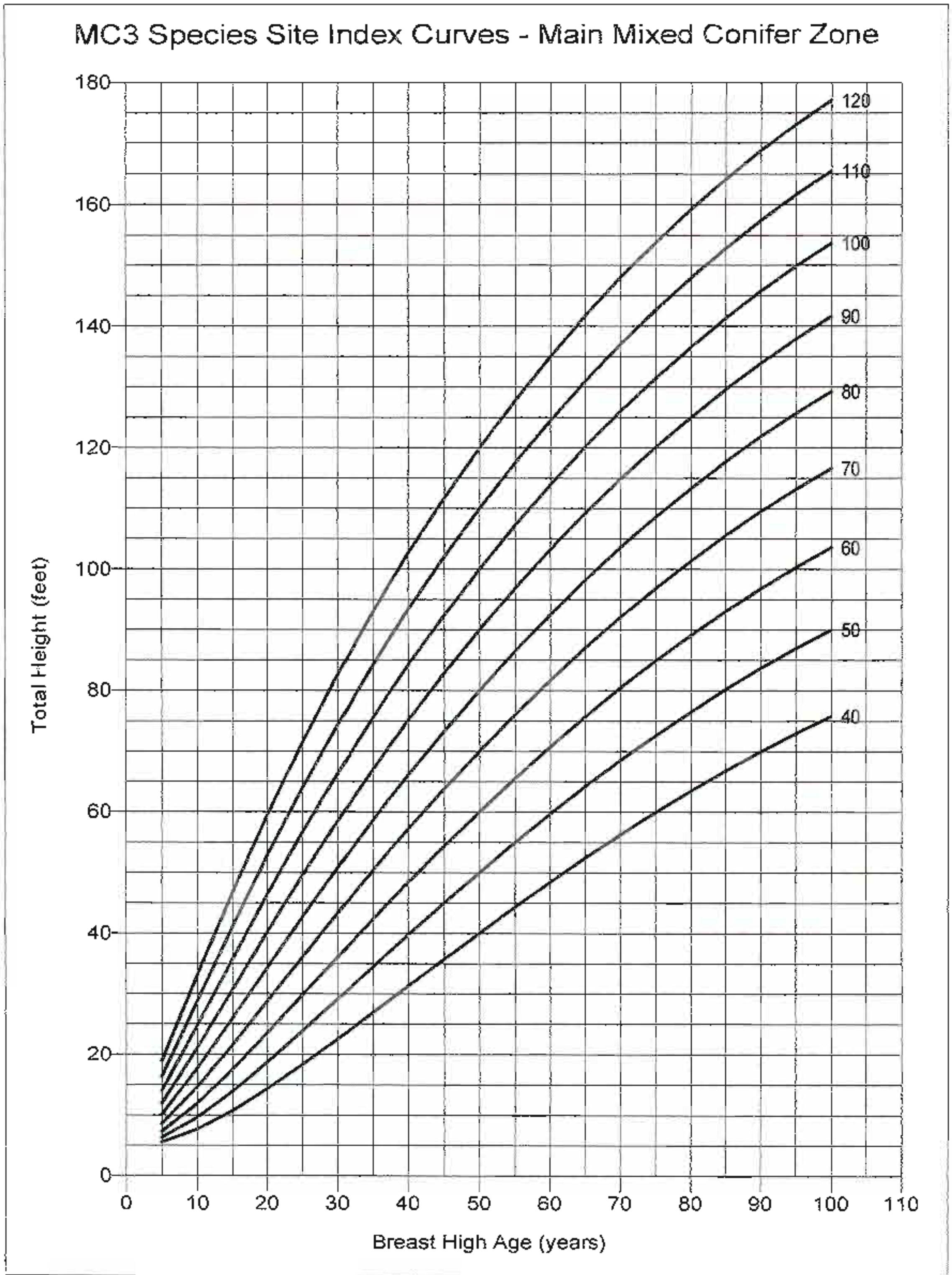

Figure I.11. *MC3 species site index curves for the MC3_CR2_MMC model.*

Table I.4. MC3 species site index table for the MC3_CR2_MMC model.

MC3 Species Site Index Table - MMC Zone (MC3_CR2_MMC)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index																
Age	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
12	8.8	10.0	11.2	12.6	14.1	15.7	17.4	19.1	21.0	22.9	24.9	27.1	29.2	31.5	33.8	36.3	38.7
14	10.0	11.4	13.0	14.6	16.3	18.2	20.1	22.2	24.3	26.5	28.8	31.2	33.6	36.1	38.7	41.4	44.1
16	11.4	13.0	14.8	16.7	18.7	20.8	23.0	25.3	27.6	30.1	32.6	35.2	37.9	40.7	43.5	46.4	49.4
18	12.8	14.7	16.7	18.8	21.1	23.4	25.8	28.4	31.0	33.7	36.4	39.3	42.2	45.2	48.2	51.3	54.5
20	14.3	16.4	18.7	21.0	23.5	26.1	28.7	31.5	34.3	37.2	40.2	43.3	46.4	49.6	52.8	56.1	59.5
22	15.8	18.2	20.7	23.3	26.0	28.8	31.7	34.6	37.7	40.8	44.0	47.2	50.5	53.9	57.3	60.8	64.4
24	17.4	20.0	22.8	25.6	28.5	31.5	34.6	37.7	41.0	44.3	47.7	51.1	54.6	58.1	61.7	65.4	69.1
26	19.1	21.9	24.8	27.9	31.0	34.2	37.5	40.8	44.3	47.8	51.3	54.9	58.6	62.3	66.0	69.9	73.7
28	20.8	23.8	27.0	30.2	33.5	36.9	40.4	43.9	47.5	51.2	54.9	58.7	62.5	66.3	70.3	74.2	78.2
30	22.5	25.7	29.1	32.5	36.0	39.6	43.3	47.0	50.7	54.6	58.4	62.3	66.3	70.3	74.4	78.4	82.6
32	24.2	27.7	31.2	34.8	38.5	42.3	46.1	50.0	53.9	57.9	61.9	65.9	70.0	74.2	78.4	82.6	86.8
34	26.0	29.6	33.3	37.2	41.0	44.9	48.9	52.9	57.0	61.1	65.3	69.5	73.7	78.0	82.3	86.6	90.9
36	27.7	31.6	35.5	39.5	43.5	47.6	51.7	55.9	60.1	64.3	68.6	72.9	77.3	81.7	86.1	90.5	94.9
38	29.5	33.5	37.6	41.7	45.9	50.2	54.4	58.8	63.1	67.5	71.9	76.3	80.8	85.3	89.8	94.3	98.8
40	31.2	35.5	39.7	44.0	48.4	52.7	57.1	61.6	66.1	70.6	75.1	79.6	84.2	88.8	93.4	98.0	102.6
42	33.0	37.4	41.8	46.3	50.8	55.3	59.8	64.4	69.0	73.6	78.2	82.8	87.5	92.2	96.9	101.6	106.3
44	34.8	39.3	43.9	48.5	53.1	57.8	62.4	67.1	71.8	76.5	81.3	86.0	90.7	95.5	100.3	105.1	109.9
46	36.5	41.2	46.0	50.7	55.4	60.2	65.0	69.8	74.6	79.4	84.2	89.1	93.9	98.8	103.6	108.5	113.3
48	38.3	43.1	48.0	52.9	57.7	62.6	67.5	72.4	77.3	82.2	87.2	92.1	97.0	101.9	106.9	111.8	116.7
50	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0
52	41.7	46.9	52.0	57.1	62.2	67.3	72.4	77.5	82.6	87.7	92.8	97.9	102.9	108.0	113.1	118.1	123.2
54	43.4	48.7	53.9	59.2	64.4	69.6	74.8	80.0	85.2	90.3	95.5	100.6	105.8	110.9	116.0	121.2	126.3
56	45.1	50.5	55.9	61.2	66.5	71.9	77.1	82.4	87.7	92.9	98.1	103.4	108.6	113.7	118.9	124.1	129.3
58	46.8	52.3	57.8	63.2	68.6	74.0	79.4	84.8	90.1	95.4	100.7	106.0	111.3	116.5	121.7	127.0	132.2
60	48.4	54.0	59.6	65.2	70.7	76.2	81.7	87.1	92.5	97.9	103.2	108.6	113.9	119.2	124.5	129.8	135.0
62	50.0	55.8	61.5	67.1	72.7	78.3	83.8	89.3	94.8	100.3	105.7	111.1	116.5	121.8	127.1	132.5	137.8
64	51.6	57.5	63.3	69.0	74.7	80.4	86.0	91.5	97.1	102.6	108.1	113.5	118.9	124.3	129.7	135.1	140.4
66	53.2	59.1	65.0	70.9	76.7	82.4	88.1	93.7	99.3	104.9	110.4	115.9	121.4	126.8	132.2	137.6	143.0
68	54.7	60.8	66.8	72.7	78.6	84.3	90.1	95.8	101.4	107.1	112.7	118.2	123.7	129.2	134.7	140.1	145.5
70	56.2	62.4	68.5	74.5	80.4	86.3	92.1	97.8	103.6	109.2	114.9	120.5	126.0	131.6	137.1	142.5	148.0
72	57.7	64.0	70.2	76.2	82.2	88.2	94.0	99.8	105.6	111.3	117.0	122.6	128.2	133.8	139.4	144.9	150.3
74	59.2	65.5	71.8	77.9	84.0	90.0	95.9	101.8	107.6	113.4	119.1	124.8	130.4	136.0	141.6	147.1	152.6
76	60.6	67.1	73.4	79.6	85.7	91.8	97.8	103.7	109.6	115.4	121.1	126.8	132.5	138.2	143.8	149.3	154.9
78	62.1	68.6	75.0	81.2	87.4	93.5	99.6	105.5	111.5	117.3	123.1	128.9	134.6	140.3	145.9	151.5	157.0
80	63.4	70.0	76.5	82.8	89.1	95.2	101.3	107.3	113.3	119.2	125.0	130.8	136.6	142.3	147.9	153.6	159.1
82	64.8	71.5	78.0	84.4	90.7	96.9	103.0	109.1	115.1	121.0	126.9	132.7	138.5	144.2	149.9	155.6	161.2
84	66.1	72.9	79.5	85.9	92.3	98.5	104.7	110.8	116.9	122.8	128.7	134.6	140.4	146.2	151.9	157.5	163.2
86	67.4	74.2	80.9	87.4	93.8	100.1	106.4	112.5	118.6	124.6	130.5	136.4	142.2	148.0	153.7	159.4	165.1
88	68.7	75.6	82.3	88.9	95.3	101.7	107.9	114.1	120.2	126.3	132.2	138.1	144.0	149.8	155.6	161.3	167.0
90	69.9	76.9	83.7	90.3	96.8	103.2	109.5	115.7	121.8	127.9	133.9	139.8	145.7	151.6	157.3	163.1	168.8
92	71.2	78.2	85.0	91.7	98.2	104.7	111.0	117.2	123.4	129.5	135.5	141.5	147.4	153.3	159.1	164.8	170.5
94	72.4	79.4	86.3	93.0	99.6	106.1	112.5	118.7	124.9	131.1	137.1	143.1	149.0	154.9	160.7	166.5	172.2
96	73.5	80.6	87.6	94.3	101.0	107.5	113.9	120.2	126.4	132.6	138.7	144.7	150.6	156.5	162.4	168.1	173.9
98	74.7	81.8	88.8	95.6	102.3	108.8	115.3	121.6	127.9	134.1	140.2	146.2	152.2	158.1	163.9	169.7	175.5
100	75.8	83.0	90.0	96.9	103.6	110.2	116.6	123.0	129.3	135.5	141.6	147.7	153.7	159.6	165.5	171.3	177.1

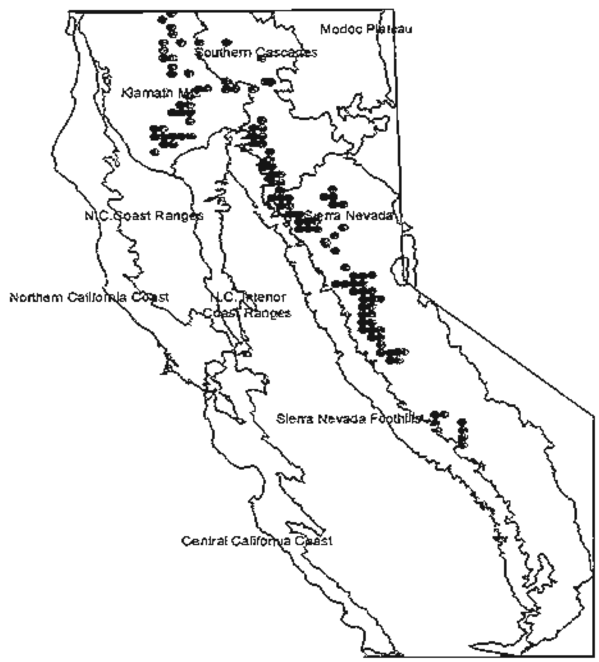

Figure I.12. *MC3 species sampling locations for the main mixed-conifer zone.*

I.2.5 MC3 Species – Other Mixed-Conifer Zone

Model Name: MC3_CR2_OMC
Model Form: CR2

Synopsis

The MC3_CR2_OMC site index model is applicable to MC3 species (ponderosa pine, interior Douglas-fir, and sugar pine) in the 'Other mixed-conifer' zone. This zone is largely the 'fringe' area of the interior mixed-conifer distribution and specific details are provided in Section 6.2.2 . The age range is approximately 10 to 100 years and the site index range is 30 – 90 feet.

Figure I.13 shows the time series data used in fitting the model. Figure I.14 shows site curve graphs. Table I.5 provides tabular values of heights by breast-high age and site index. Figure I.15 maps the MC3 species sampling locations in the other mixed conifer zone.

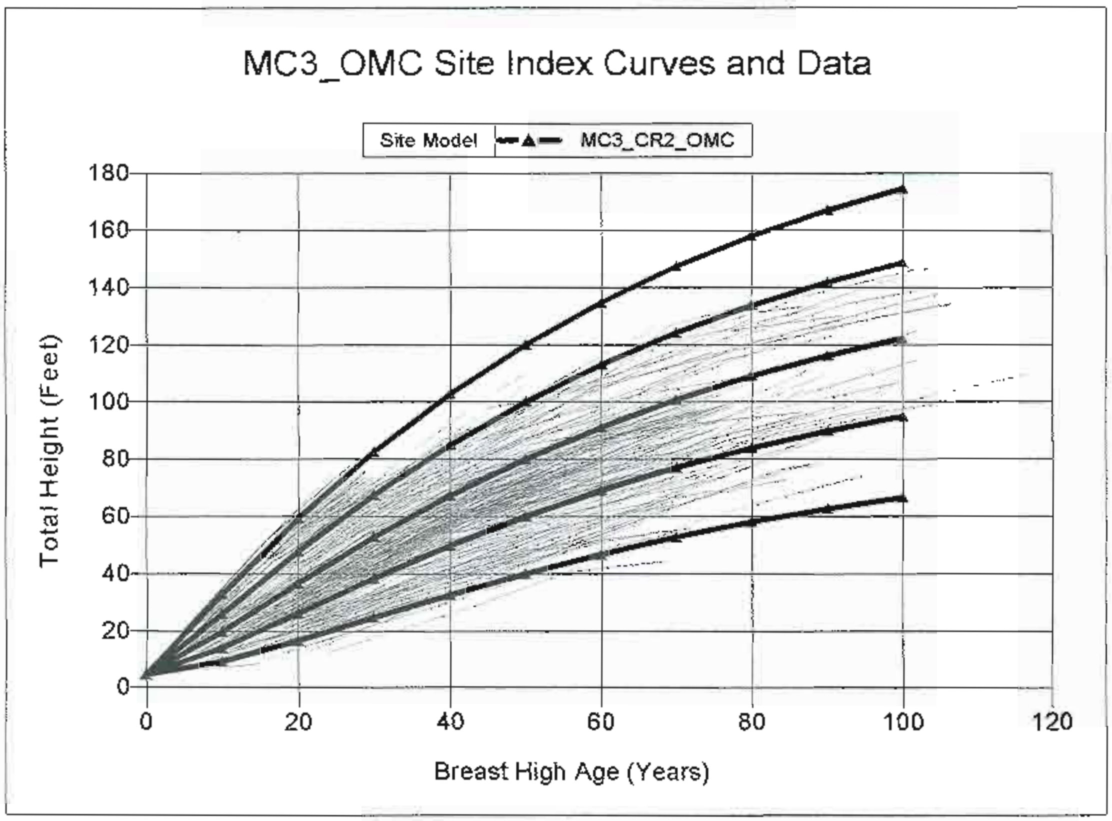

Figure I.13. *MC3 Species height growth data used in model construction for the other mixed-conifer zone.*

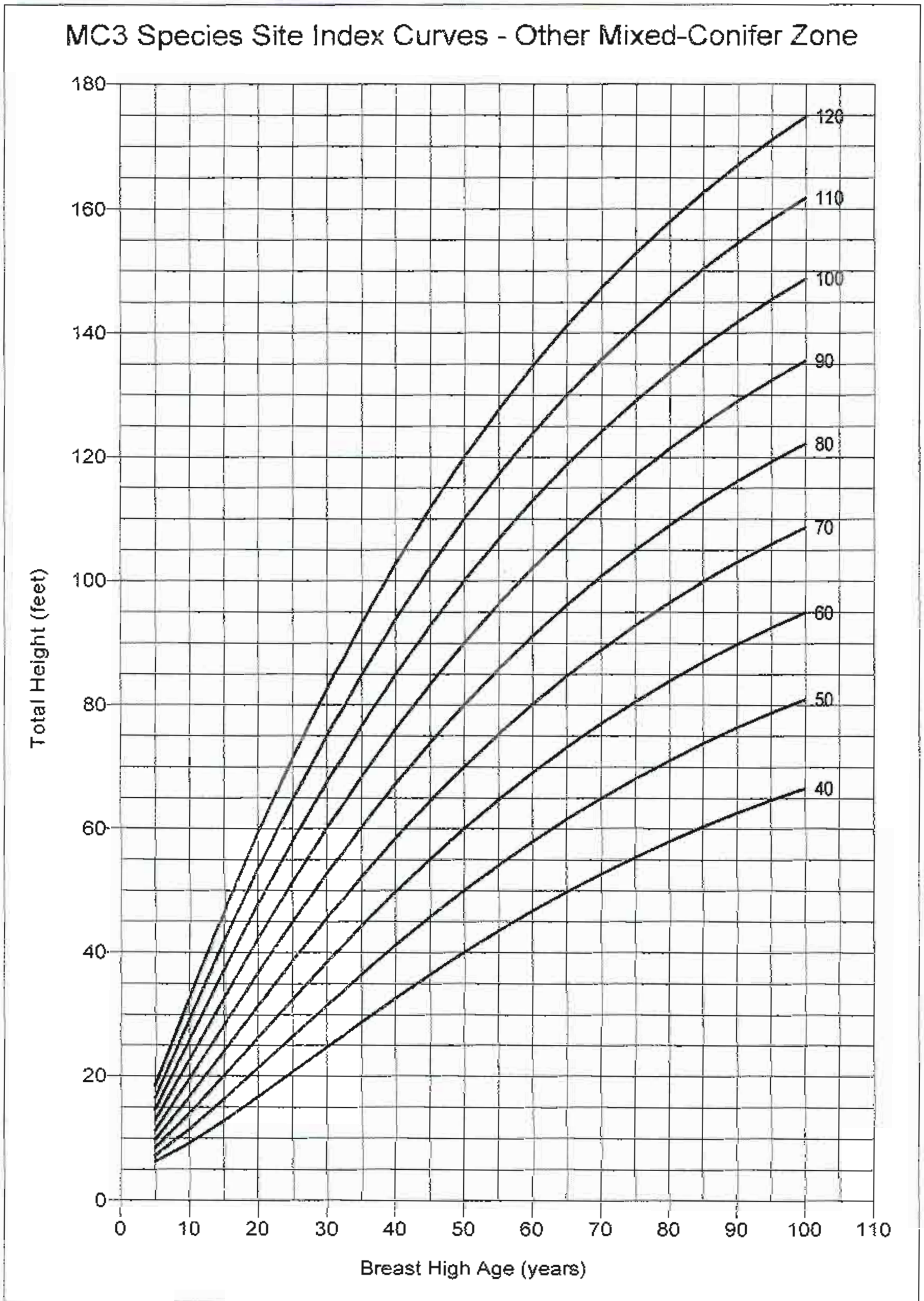

Figure I.14. *MC3 species site index curves for the MC3_CR2_OMC model.*

Table I.5. MC3 species site index table for the MC3_CR2_OMC model.

MC3 Species Site Index Table - OMC Zone (MC3_CR2_OMC)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index																
Age	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
12	10.5	11.9	13.3	14.8	16.3	17.9	19.6	21.3	23.0	24.8	26.6	28.5	30.4	32.3	34.3	36.3	38.3
14	12.0	13.6	15.2	17.0	18.8	20.6	22.5	24.4	26.4	28.5	30.6	32.7	34.8	37.0	39.2	41.5	43.7
16	13.5	15.3	17.2	19.2	21.2	23.3	25.5	27.6	29.9	32.2	34.5	36.8	39.2	41.6	44.1	46.6	49.1
18	15.0	17.1	19.2	21.5	23.7	26.0	28.4	30.8	33.3	35.8	38.3	40.9	43.5	46.2	48.8	51.5	54.3
20	16.6	18.9	21.3	23.7	26.2	28.8	31.3	34.0	36.7	39.4	42.1	44.9	47.7	50.6	53.5	56.4	59.3
22	18.2	20.7	23.3	26.0	28.7	31.5	34.3	37.1	40.0	42.9	45.9	48.9	51.9	54.9	58.0	61.1	64.2
24	19.8	22.6	25.4	28.2	31.2	34.1	37.1	40.2	43.3	46.4	49.5	52.7	55.9	59.2	62.4	65.7	69.0
26	21.5	24.4	27.4	30.5	33.6	36.8	40.0	43.2	46.5	49.8	53.1	56.5	59.9	63.3	66.7	70.2	73.7
28	23.1	26.2	29.5	32.7	36.0	39.4	42.8	46.2	49.7	53.1	56.7	60.2	63.8	67.3	70.9	74.6	78.2
30	24.7	28.1	31.5	34.9	38.4	42.0	45.5	49.1	52.8	56.4	60.1	63.8	67.5	71.3	75.0	78.8	82.6
32	26.3	29.9	33.5	37.1	40.8	44.5	48.2	52.0	55.8	59.6	63.4	67.3	71.2	75.1	79.0	82.9	86.9
34	27.9	31.6	35.4	39.2	43.1	47.0	50.9	54.8	58.7	62.7	66.7	70.7	74.8	78.8	82.9	86.9	91.0
36	29.5	33.4	37.4	41.3	45.4	49.4	53.5	57.5	61.6	65.8	69.9	74.1	78.2	82.4	86.6	90.8	95.1
38	31.1	35.1	39.3	43.4	47.6	51.8	56.0	60.2	64.5	68.7	73.0	77.3	81.6	85.9	90.3	94.6	99.0
40	32.6	36.9	41.1	45.4	49.8	54.1	58.5	62.8	67.2	71.6	76.0	80.5	84.9	89.4	93.8	98.3	102.7
42	34.1	38.5	43.0	47.4	51.9	56.4	60.9	65.4	69.9	74.5	79.0	83.5	88.1	92.7	97.2	101.8	106.4
44	35.6	40.2	44.8	49.4	54.0	58.6	63.3	67.9	72.5	77.2	81.9	86.5	91.2	95.9	100.6	105.3	110.0
46	37.1	41.8	46.6	51.3	56.0	60.8	65.6	70.3	75.1	79.9	84.7	89.4	94.2	99.0	103.8	108.6	113.4
48	38.6	43.4	48.3	53.2	58.0	62.9	67.8	72.7	77.6	82.5	87.4	92.3	97.2	102.1	107.0	111.9	116.8
50	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0
52	41.4	46.5	51.7	56.8	61.9	67.0	72.1	77.2	82.4	87.5	92.6	97.7	102.8	107.9	113.0	118.0	123.1
54	42.8	48.0	53.3	58.5	63.8	69.0	74.2	79.4	84.6	89.8	95.0	100.2	105.4	110.6	115.8	121.0	126.2
56	44.1	49.5	54.9	60.2	65.6	70.9	76.2	81.6	86.9	92.2	97.5	102.8	108.0	113.3	118.6	123.9	129.1
58	45.4	50.9	56.4	61.9	67.3	72.8	78.2	83.6	89.0	94.4	99.8	105.2	110.6	115.9	121.3	126.6	132.0
60	46.7	52.3	57.9	63.5	69.1	74.6	80.1	85.6	91.1	96.6	102.1	107.6	113.0	118.5	123.9	129.3	134.7
62	48.0	53.7	59.4	65.1	70.7	76.4	82.0	87.6	93.2	98.7	104.3	109.8	115.4	120.9	126.4	131.9	137.4
64	49.2	55.0	60.8	66.6	72.4	78.1	83.8	89.5	95.2	100.8	106.4	112.1	117.7	123.3	128.9	134.4	140.0
66	50.4	56.3	62.2	68.1	74.0	79.8	85.6	91.3	97.1	102.8	108.5	114.2	119.9	125.6	131.2	136.9	142.5
68	51.6	57.6	63.6	69.6	75.5	81.4	87.3	93.1	98.9	104.8	110.5	116.3	122.1	127.8	133.5	139.2	144.9
70	52.7	58.8	64.9	71.0	77.0	83.0	88.9	94.9	100.8	106.6	112.5	118.3	124.2	130.0	135.8	141.5	147.3
72	53.8	60.0	66.2	72.4	78.5	84.5	90.5	96.5	102.5	108.5	114.4	120.3	126.2	132.1	137.9	143.8	149.6
74	54.9	61.2	67.5	73.7	79.9	86.0	92.1	98.2	104.2	110.2	116.2	122.2	128.2	134.1	140.0	145.9	151.8
76	56.0	62.4	68.7	75.0	81.3	87.5	93.6	99.8	105.9	112.0	118.0	124.0	130.1	136.1	142.0	148.0	153.9
78	57.0	63.5	69.9	76.3	82.6	88.9	95.1	101.3	107.5	113.6	119.7	125.8	131.9	138.0	144.0	150.0	156.0
80	58.0	64.6	71.1	77.5	83.9	90.2	96.5	102.8	109.0	115.2	121.4	127.6	133.7	139.8	145.9	151.9	158.0
82	59.0	65.6	72.2	78.7	85.2	91.6	97.9	104.3	110.6	116.8	123.0	129.2	135.4	141.6	147.7	153.8	159.9
84	59.9	66.6	73.3	79.9	86.4	92.9	99.3	105.7	112.0	118.3	124.6	130.9	137.1	143.3	149.5	155.6	161.8
86	60.8	67.6	74.3	81.0	87.6	94.1	100.6	107.0	113.4	119.8	126.1	132.4	138.7	145.0	151.2	157.4	163.6
88	61.7	68.6	75.4	82.1	88.7	95.3	101.9	108.4	114.8	121.2	127.6	134.0	140.3	146.6	152.9	159.1	165.4
90	62.6	69.5	76.4	83.1	89.8	96.5	103.1	109.6	116.1	122.6	129.0	135.5	141.8	148.2	154.5	160.8	167.0
92	63.4	70.4	77.3	84.2	90.9	97.6	104.3	110.9	117.4	124.0	130.4	136.9	143.3	149.7	156.0	162.4	168.7
94	64.3	71.3	78.3	85.2	92.0	98.7	105.4	112.1	118.7	125.3	131.8	138.3	144.7	151.2	157.6	163.9	170.3
96	65.1	72.2	79.2	86.1	93.0	99.8	106.6	113.3	119.9	126.5	133.1	139.6	146.1	152.6	159.0	165.4	171.8
98	65.8	73.0	80.1	87.1	94.0	100.9	107.6	114.4	121.1	127.7	134.3	140.9	147.4	154.0	160.4	166.9	173.3
100	66.6	73.8	81.0	88.0	95.0	101.9	108.7	115.5	122.2	128.9	135.6	142.2	148.7	155.3	161.8	168.3	174.7

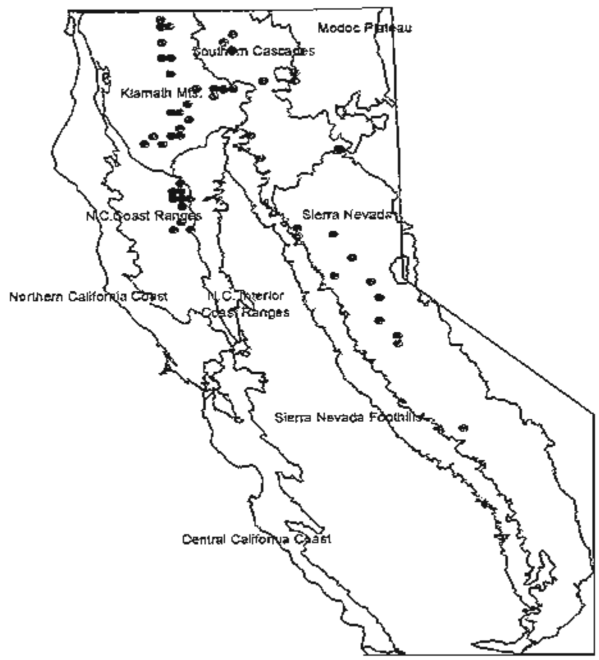

Figure I.15. *MC3 species sampling locations for the other mixed-conifer zone.*

I.2.6 MC3 Species – McCloud Area Zone

Model Name: MC3_CR2_MA
Model Form: CR2

Synopsis

The MC3_CR2_MA site index model is applicable to MC3 species (ponderosa pine, interior Douglas-fir, and sugar pine) in the McCloud Area mixed-conifer' zone. This zone is largely located in the McCloud flats area of the interior mixed-conifer distribution and specific details are provided in Section 6.2.2 . The age range is approximately 10 to 100 years and the site index range is 60 – 120 feet.

Figure I.16 shows the time series data used in fitting the model. Figure I.17 shows site curve graphs. Table I.6 provides tabular values of heights by breast-high age and site index. Figure I.18 maps the MC3 species sampling locations in the McCloud area mixed-conifer zone.

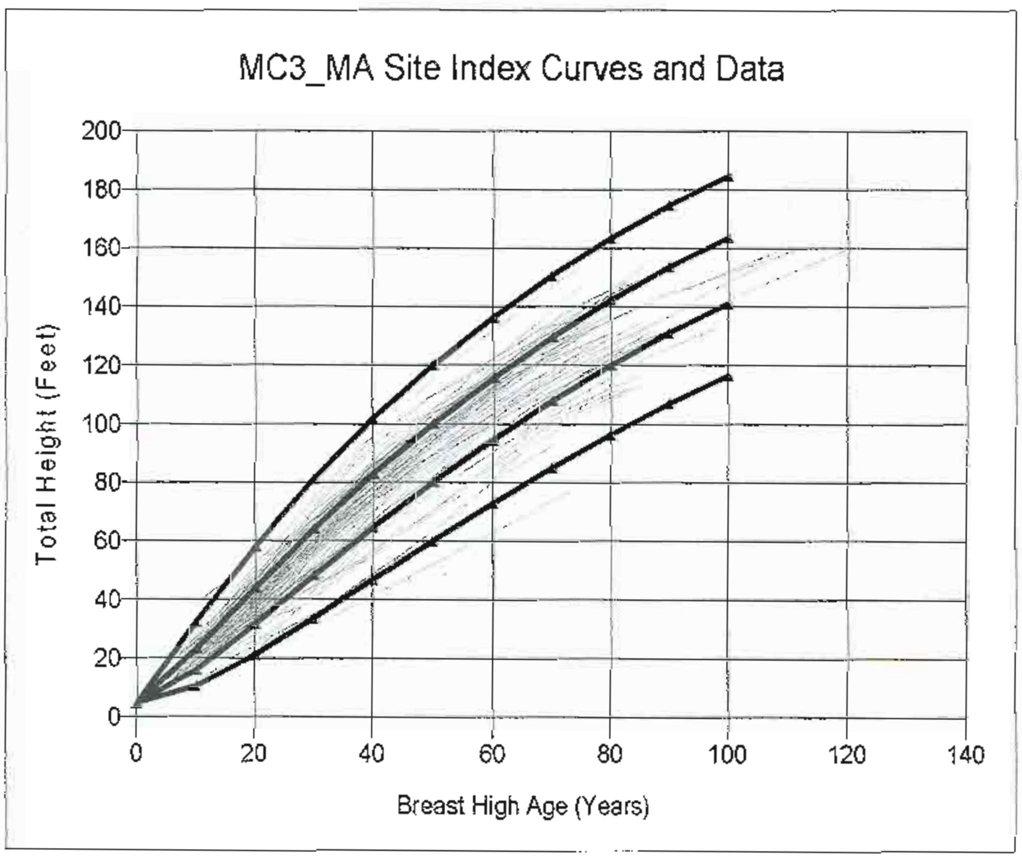

Figure 1.16. *MC3 Species height growth data used in model construction for the McCloud area mixed-conifer zone.*

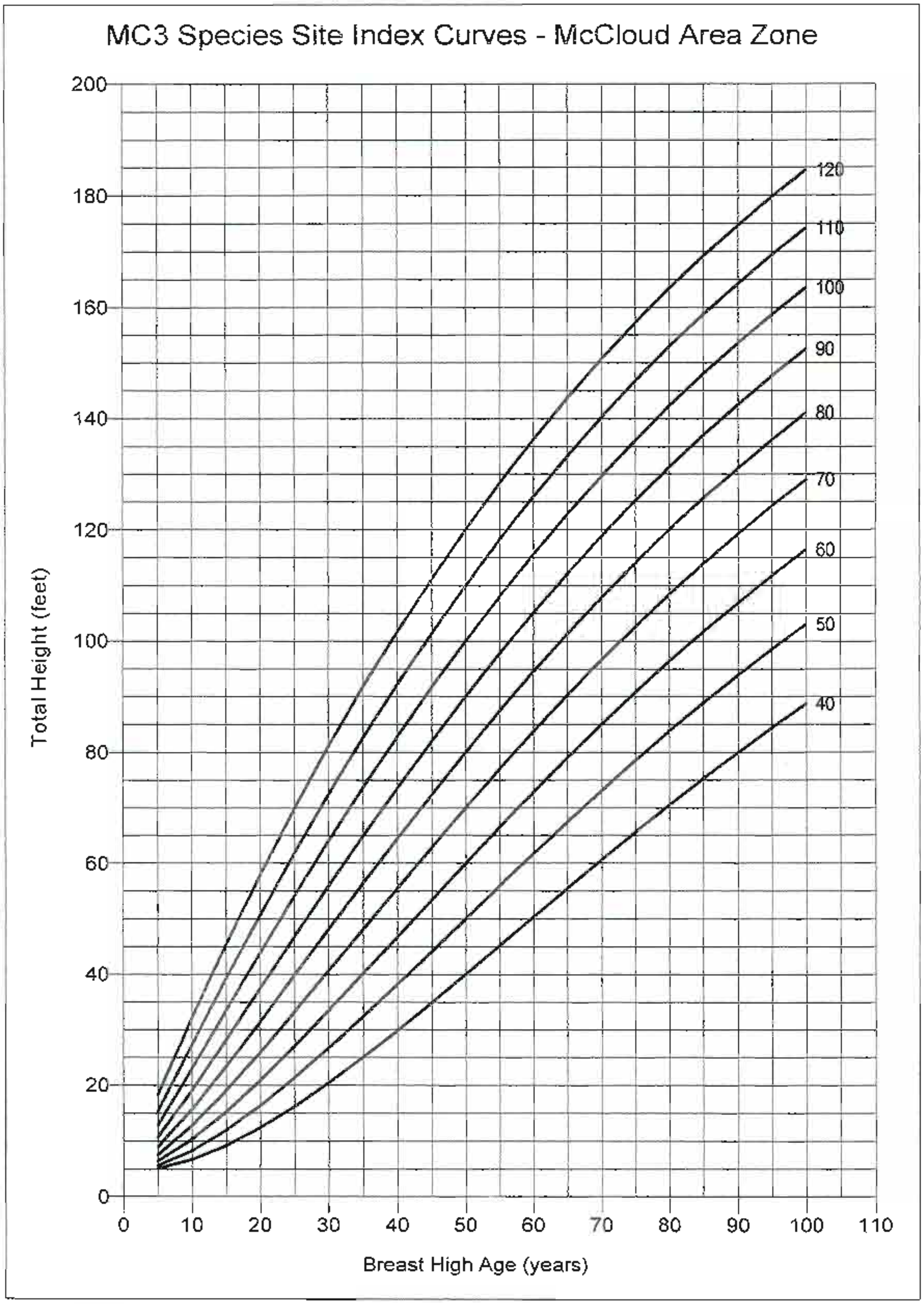

Figure I.17. *MC3 species site index curves for the MC3_CR2_MA model.*

Table I.6. MC3 species site index table for the MC3_CR2_MA model.

MC3 Species Site Index Table - MA Zone (MC3_CR2_MA)

Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index																
Age	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
12	7.6	8.5	9.6	10.8	12.2	13.6	15.2	16.9	18.7	20.6	22.7	24.8	27.1	29.5	32.1	34.7	37.5
14	8.6	9.8	11.1	12.6	14.2	15.9	17.7	19.7	21.8	24.0	26.3	28.8	31.3	34.0	36.8	39.7	42.7
16	9.8	11.2	12.8	14.5	16.3	18.3	20.4	22.6	24.9	27.4	30.0	32.7	35.5	38.4	41.5	44.6	47.9
18	11.0	12.7	14.5	16.5	18.5	20.8	23.1	25.6	28.2	30.9	33.7	36.6	39.7	42.8	46.1	49.5	52.9
20	12.4	14.3	16.4	18.6	20.9	23.3	25.9	28.6	31.5	34.4	37.4	40.6	43.9	47.2	50.7	54.2	57.9
22	13.9	16.0	18.3	20.7	23.3	26.0	28.8	31.7	34.8	37.9	41.2	44.5	48.0	51.5	55.2	58.9	62.7
24	15.4	17.8	20.3	23.0	25.8	28.7	31.7	34.8	38.1	41.4	44.9	48.4	52.1	55.8	59.6	63.5	67.4
26	17.0	19.6	22.4	25.3	28.3	31.4	34.6	38.0	41.4	45.0	48.6	52.3	56.1	60.0	63.9	68.0	72.1
28	18.7	21.5	24.5	27.6	30.9	34.2	37.6	41.1	44.8	48.5	52.3	56.1	60.1	64.1	68.2	72.4	76.6
30	20.4	23.5	26.7	30.0	33.5	37.0	40.6	44.3	48.1	52.0	55.9	59.9	64.0	68.2	72.4	76.7	81.0
32	22.2	25.5	28.9	32.5	36.1	39.8	43.6	47.5	51.4	55.4	59.5	63.7	67.9	72.2	76.5	80.9	85.3
34	24.1	27.6	31.2	34.9	38.7	42.6	46.6	50.6	54.7	58.9	63.1	67.4	71.7	76.1	80.5	85.0	89.6
36	26.0	29.7	33.5	37.4	41.4	45.4	49.6	53.7	58.0	62.3	66.6	71.0	75.5	80.0	84.5	89.1	93.7
38	27.9	31.8	35.8	39.9	44.1	48.3	52.5	56.9	61.2	65.6	70.1	74.6	79.2	83.8	88.4	93.0	97.7
40	29.9	34.0	38.2	42.4	46.7	51.1	55.5	60.0	64.4	69.0	73.6	78.2	82.8	87.5	92.2	96.9	101.7
42	31.8	36.2	40.5	44.9	49.4	53.9	58.4	63.0	67.6	72.3	76.9	81.6	86.4	91.1	95.9	100.7	105.5
44	33.9	38.4	42.9	47.5	52.1	56.7	61.4	66.1	70.8	75.5	80.3	85.1	89.9	94.7	99.5	104.4	109.3
46	35.9	40.6	45.3	50.0	54.7	59.5	64.3	69.1	73.9	78.7	83.6	88.4	93.3	98.2	103.1	108.0	112.9
48	37.9	42.8	47.6	52.5	57.4	62.3	67.2	72.1	77.0	81.9	86.8	91.7	96.7	101.6	106.6	111.5	116.5
50	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0
52	42.1	47.2	52.4	57.5	62.6	67.7	72.8	77.9	83.0	88.1	93.1	98.2	103.2	108.3	113.3	118.4	123.4
54	44.1	49.4	54.7	60.0	65.2	70.4	75.6	80.8	85.9	91.1	96.2	101.3	106.4	111.5	116.6	121.7	126.7
56	46.2	51.7	57.1	62.4	67.8	73.1	78.4	83.6	88.8	94.0	99.2	104.4	109.5	114.7	119.8	124.9	130.0
58	48.3	53.9	59.4	64.9	70.3	75.7	81.1	86.4	91.7	97.0	102.2	107.4	112.6	117.8	122.9	128.0	133.2
60	50.4	56.1	61.7	67.3	72.8	78.3	83.8	89.1	94.5	99.8	105.1	110.4	115.6	120.8	126.0	131.1	136.3
62	52.4	58.3	64.0	69.7	75.3	80.9	86.4	91.9	97.3	102.6	108.0	113.3	118.5	123.8	129.0	134.1	139.3
64	54.5	60.5	66.3	72.1	77.8	83.4	89.0	94.5	100.0	105.4	110.8	116.1	121.4	126.6	131.9	137.1	142.2
66	56.5	62.6	68.6	74.5	80.2	85.9	91.6	97.1	102.7	108.1	113.5	118.9	124.2	129.5	134.7	139.9	145.1
68	58.6	64.8	70.8	76.8	82.6	88.4	94.1	99.7	105.3	110.8	116.2	121.6	126.9	132.2	137.5	142.7	147.9
70	60.6	66.9	73.1	79.1	85.0	90.8	96.6	102.3	107.8	113.4	118.9	124.3	129.6	135.0	140.2	145.5	150.6
72	62.6	69.0	75.3	81.4	87.3	93.2	99.0	104.7	110.4	115.9	121.4	126.9	132.3	137.6	142.9	148.1	153.3
74	64.6	71.1	77.4	83.6	89.7	95.6	101.4	107.2	112.9	118.5	124.0	129.4	134.8	140.2	145.5	150.7	155.9
76	66.6	73.2	79.6	85.8	91.9	97.9	103.8	109.6	115.3	120.9	126.5	131.9	137.4	142.7	148.0	153.3	158.5
78	68.6	75.2	81.7	88.0	94.2	100.2	106.1	112.0	117.7	123.3	128.9	134.4	139.8	145.2	150.5	155.8	161.0
80	70.5	77.3	83.8	90.2	96.4	102.5	108.4	114.3	120.0	125.7	131.3	136.8	142.2	147.6	152.9	158.2	163.4
82	72.4	79.2	85.9	92.3	98.5	104.7	110.7	116.5	122.3	128.0	133.6	139.1	144.6	150.0	155.3	160.5	165.7
84	74.3	81.2	87.9	94.4	100.7	106.8	112.9	118.8	124.6	130.3	135.9	141.4	146.9	152.3	157.6	162.8	168.0
86	76.2	83.2	89.9	96.4	102.8	109.0	115.0	121.0	126.8	132.5	138.1	143.7	149.1	154.5	159.8	165.1	170.3
88	78.1	85.1	91.9	98.4	104.8	111.1	117.1	123.1	128.9	134.7	140.3	145.9	151.3	156.7	162.0	167.3	172.5
90	79.9	87.0	93.8	100.4	106.9	113.1	119.2	125.2	131.1	136.8	142.5	148.0	153.5	158.9	164.2	169.4	174.6
92	81.7	88.9	95.7	102.4	108.9	115.1	121.3	127.3	133.1	138.9	144.6	150.1	155.6	161.0	166.3	171.5	176.7
94	83.5	90.7	97.6	104.3	110.8	117.1	123.3	129.3	135.2	140.9	146.6	152.2	157.6	163.0	168.3	173.6	178.7
96	85.3	92.5	99.5	106.2	112.7	119.1	125.2	131.3	137.2	142.9	148.6	154.2	159.7	165.0	170.3	175.6	180.7
98	87.0	94.3	101.3	108.1	114.6	121.0	127.2	133.2	139.1	144.9	150.6	156.1	161.6	167.0	172.3	177.5	182.7
100	88.7	96.1	103.1	109.9	116.5	122.8	129.1	135.1	141.0	146.8	152.5	158.1	163.5	168.9	174.2	179.4	184.6

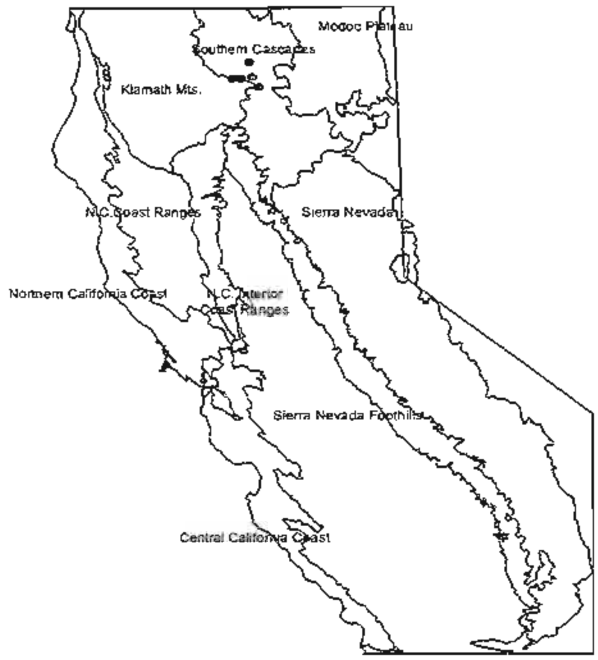

Figure I.18. *MC3 species sampling locations for the McCloud area mixed-conifer zone.*

I.2.7 White fir

Model Name: WF_CR2_Ca
Model Form: CR2

Synopsis

The WF_CR2_Ca site index model is applicable to white fir anywhere it grows in the state. The age range is approximately 10 to 100 years and the site index range is 40 – 110 feet.

Figure I.19 shows the time series data used in fitting the model. Figure I.20 shows site curve graphs. Table I.7 provides tabular values of heights by breast-high age and site index. Figure I.20 maps the statewide white fir sampling locations.

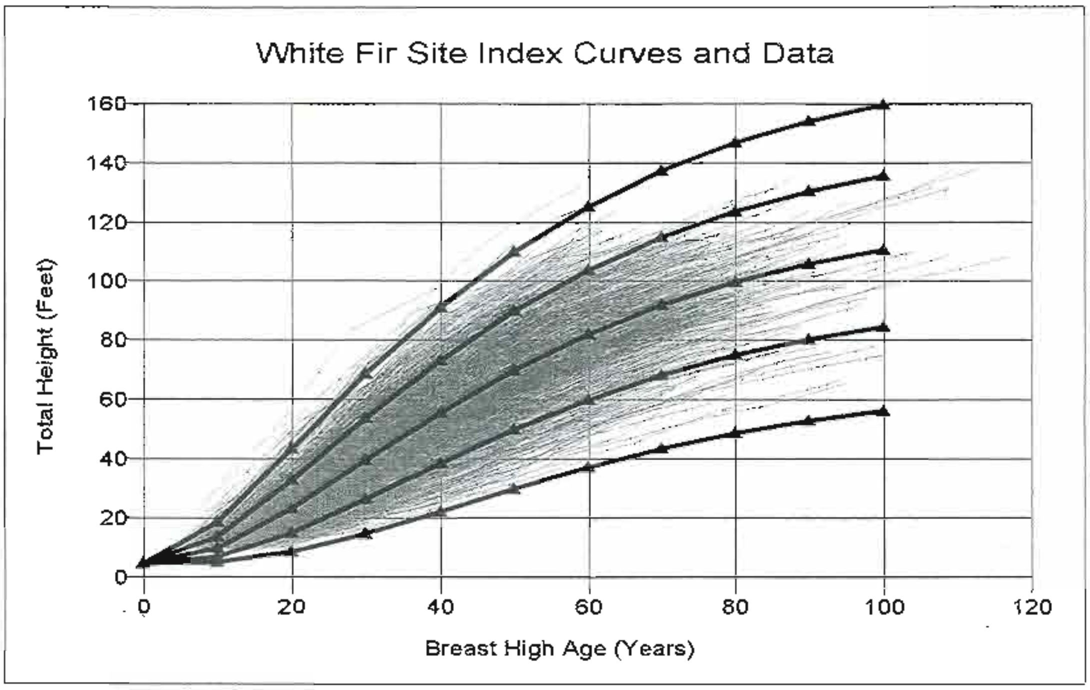

Figure I.19. *White fir height growth data used in model construction.*

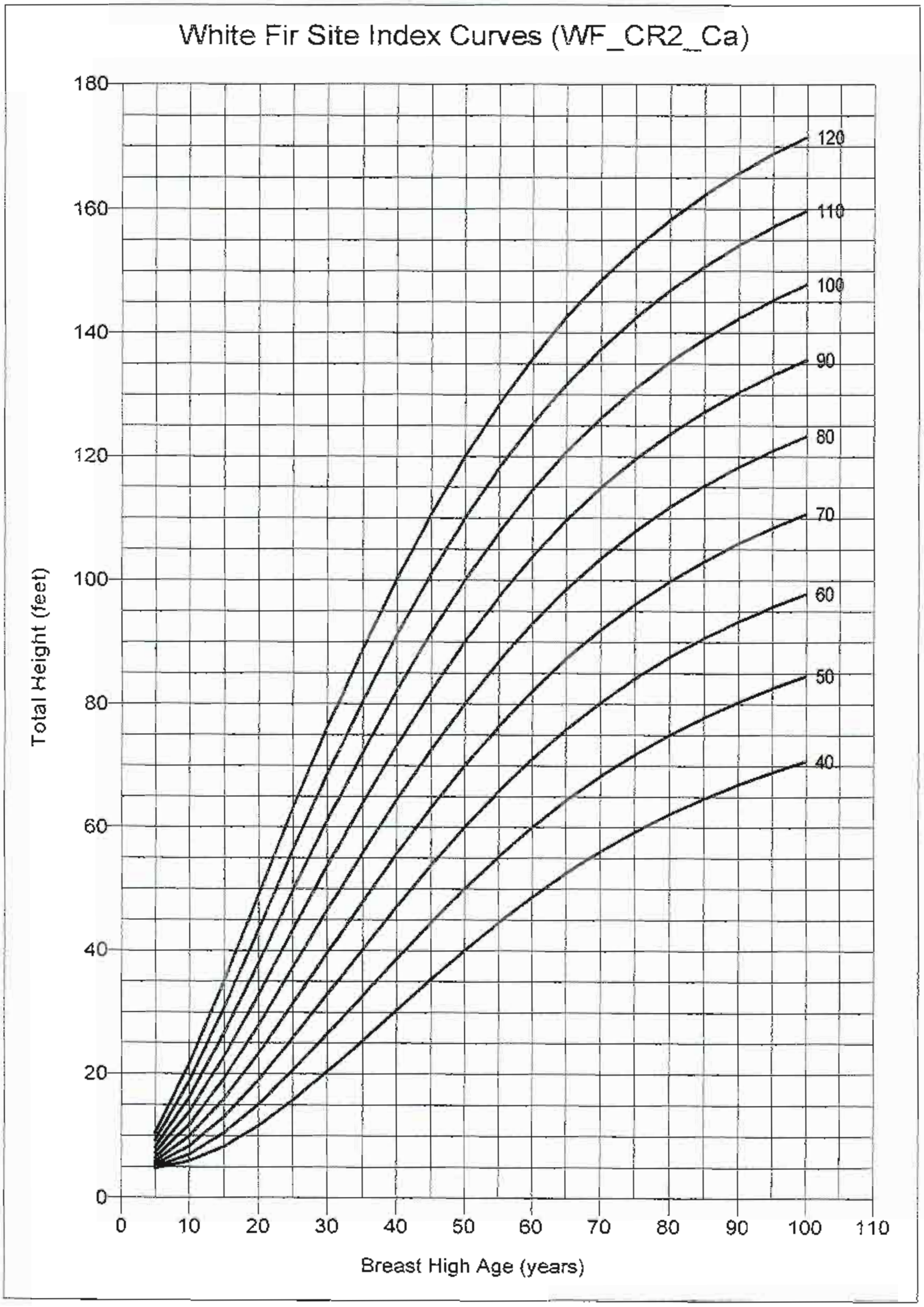

Figure I.20. *White fir site index curves for the WF_CR2_Ca model.*

Table I.7. White fir site index table for the WF_CR2_Ca model.

White Fir Site Index Table (WF_CR2_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index																
Age	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
12	10.5	11.3	12.2	13.0	13.9	14.7	15.6	16.4	17.2	18.1	18.9	19.8	20.6	21.5	22.3	23.2	24.0
14	12.0	13.1	14.1	15.2	16.3	17.3	18.4	19.4	20.5	21.6	22.6	23.7	24.7	25.8	26.9	27.9	29.0
16	13.6	14.9	16.2	17.5	18.8	20.0	21.3	22.6	23.9	25.2	26.5	27.8	29.0	30.3	31.6	32.9	34.2
18	15.3	16.8	18.3	19.8	21.3	22.8	24.4	25.9	27.4	28.9	30.4	31.9	33.4	35.0	36.5	38.0	39.5
20	16.9	18.7	20.4	22.2	23.9	25.7	27.4	29.2	30.9	32.7	34.4	36.2	37.9	39.7	41.4	43.2	44.9
22	18.6	20.6	22.6	24.6	26.6	28.5	30.5	32.5	34.5	36.5	38.5	40.5	42.5	44.4	46.4	48.4	50.4
24	20.3	22.5	24.7	27.0	29.2	31.4	33.6	35.9	38.1	40.3	42.5	44.8	47.0	49.2	51.4	53.7	55.9
26	22.0	24.4	26.9	29.4	31.8	34.3	36.8	39.2	41.7	44.1	46.6	49.1	51.5	54.0	56.4	58.9	61.4
28	23.6	26.3	29.0	31.7	34.4	37.1	39.8	42.5	45.2	47.9	50.6	53.3	56.0	58.7	61.4	64.1	66.8
30	25.3	28.2	31.2	34.1	37.0	40.0	42.9	45.8	48.7	51.7	54.6	57.5	60.5	63.4	66.3	69.2	72.2
32	26.9	30.1	33.2	36.4	39.6	42.7	45.9	49.0	52.2	55.4	58.5	61.7	64.8	68.0	71.2	74.3	77.5
34	28.5	31.9	35.3	38.7	42.1	45.4	48.8	52.2	55.6	59.0	62.4	65.8	69.1	72.5	75.9	79.3	82.7
36	30.1	33.7	37.3	40.9	44.5	48.1	51.7	55.3	58.9	62.5	66.1	69.7	73.4	77.0	80.6	84.2	87.8
38	31.6	35.4	39.3	43.1	46.9	50.7	54.6	58.4	62.2	66.0	69.8	73.7	77.5	81.3	85.1	88.9	92.8
40	33.1	37.2	41.2	45.2	49.2	53.3	57.3	61.3	65.4	69.4	73.4	77.5	81.5	85.5	89.6	93.6	97.6
42	34.6	38.8	43.1	47.3	51.5	55.8	60.0	64.2	68.5	72.7	76.9	81.2	85.4	89.7	93.9	98.1	102.4
44	36.0	40.4	44.9	49.3	53.7	58.2	62.6	67.0	71.5	75.9	80.4	84.8	89.2	93.7	98.1	102.5	107.0
46	37.4	42.0	46.6	51.3	55.9	60.5	65.2	69.8	74.4	79.0	83.7	88.3	92.9	97.6	102.2	106.8	111.5
48	38.7	43.5	48.3	53.2	58.0	62.8	67.6	72.4	77.3	82.1	86.9	91.7	96.5	101.3	106.2	111.0	115.8
50	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0
52	41.3	46.4	51.6	56.8	62.0	67.1	72.3	77.5	82.7	87.8	93.0	98.2	103.4	108.5	113.7	118.9	124.1
54	42.5	47.8	53.2	58.5	63.8	69.2	74.5	79.9	85.2	90.6	95.9	101.3	106.6	112.0	117.3	122.7	128.0
56	43.6	49.1	54.7	60.2	65.7	71.2	76.7	82.2	87.7	93.2	98.7	104.3	109.8	115.3	120.8	126.3	131.8
58	44.8	50.4	56.1	61.8	67.4	73.1	78.8	84.4	90.1	95.8	101.5	107.1	112.8	118.5	124.1	129.8	135.5
60	45.8	51.7	57.5	63.3	69.1	75.0	80.8	86.6	92.4	98.3	104.1	109.9	115.7	121.5	127.4	133.2	139.0
62	46.9	52.9	58.8	64.8	70.8	76.7	82.7	88.7	94.7	100.6	106.6	112.6	118.5	124.5	130.5	136.4	142.4
64	47.9	54.0	60.1	66.2	72.4	78.5	84.6	90.7	96.8	102.9	109.0	115.1	121.3	127.4	133.5	139.6	145.7
66	48.9	55.1	61.4	67.6	73.9	80.1	86.4	92.6	98.9	105.1	111.4	117.6	123.9	130.1	136.4	142.6	148.9
68	49.8	56.2	62.6	68.9	75.3	81.7	88.1	94.5	100.9	107.2	113.6	120.0	126.4	132.8	139.1	145.5	151.9
70	50.7	57.2	63.7	70.2	76.7	83.2	89.7	96.3	102.8	109.3	115.8	122.3	128.8	135.3	141.8	148.3	154.8
72	51.6	58.2	64.8	71.5	78.1	84.7	91.3	98.0	104.6	111.2	117.9	124.5	131.1	137.7	144.4	151.0	157.6
74	52.4	59.1	65.9	72.6	79.4	86.1	92.9	99.6	106.4	113.1	119.8	126.6	133.3	140.1	146.8	153.6	160.3
76	53.2	60.0	66.9	73.8	80.6	87.5	94.3	101.2	108.0	114.9	121.8	128.6	135.5	142.3	149.2	156.0	162.9
78	54.0	60.9	67.9	74.8	81.8	88.8	95.7	102.7	109.7	116.6	123.6	130.6	137.5	144.5	151.5	158.4	165.4
80	54.7	61.8	68.8	75.9	83.0	90.0	97.1	104.2	111.2	118.3	125.4	132.4	139.5	146.6	153.6	160.7	167.8
82	55.4	62.6	69.7	76.9	84.1	91.2	98.4	105.6	112.7	119.9	127.1	134.2	141.4	148.6	155.7	162.9	170.1
84	56.1	63.3	70.6	77.8	85.1	92.4	99.6	106.9	114.1	121.4	128.7	135.9	143.2	150.5	157.7	165.0	172.2
86	56.7	64.1	71.4	78.8	86.1	93.5	100.8	108.2	115.5	122.9	130.2	137.6	144.9	152.3	159.6	167.0	174.3
88	57.3	64.8	72.2	79.6	87.1	94.5	102.0	109.4	116.8	124.3	131.7	139.2	146.6	154.0	161.5	168.9	176.3
90	57.9	65.4	73.0	80.5	88.0	95.5	103.0	110.6	118.1	125.6	133.1	140.7	148.2	155.7	163.2	170.8	178.3
92	58.5	66.1	73.7	81.3	88.9	96.5	104.1	111.7	119.3	126.9	134.5	142.1	149.7	157.3	164.9	172.5	180.1
94	59.0	66.7	74.4	82.1	89.7	97.4	105.1	112.8	120.5	128.1	135.8	143.5	151.2	158.8	166.5	174.2	181.9
96	59.5	67.3	75.0	82.8	90.5	98.3	106.1	113.8	121.6	129.3	137.1	144.8	152.6	160.3	168.1	175.8	183.6
98	60.0	67.9	75.7	83.5	91.3	99.1	107.0	114.8	122.6	130.4	138.3	146.1	153.9	161.7	169.5	177.4	185.2
100	60.5	68.4	76.3	84.2	92.1	100.0	107.8	115.7	123.6	131.5	139.4	147.3	155.2	163.1	171.0	178.8	186.7

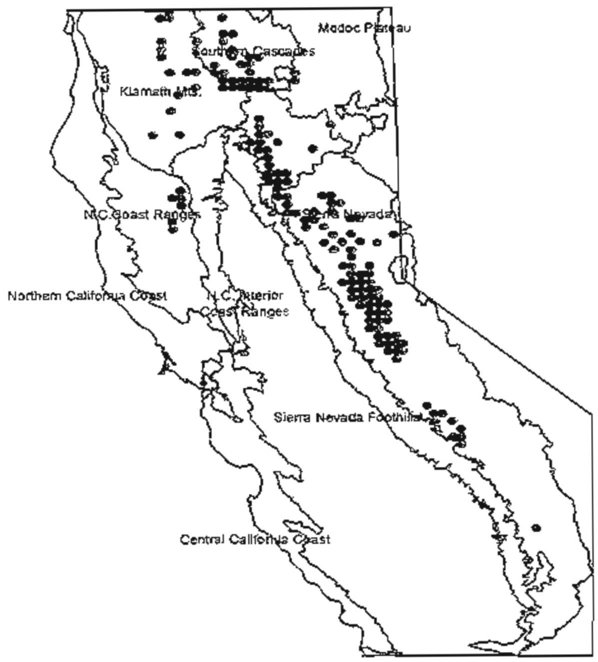

Figure I.21. *White fir sampling locations in California.*

I.2.8 Red Fir

Model Name: RF_KP1_Ca
Model Form: KP1

Synopsis

The red fir site index model RF_KP1_Ca is applicable to red fir anywhere it is found in California and Southern Oregon. The applicable age range is nominally 10 – 100 years and the site index range is 20 - 90 feet. In the unlikely event that site indices over 90 feet are encountered, white fir site index curves (WF_CR2_Ca) should be substituted.

Figure I.22 shows the time series data used in fitting the model. Figure I.23 shows site curve graphs. Table I.8 provides tabular values of heights by breast-high age and site index. Figure I.24 maps the state-wide red fir sampling locations.

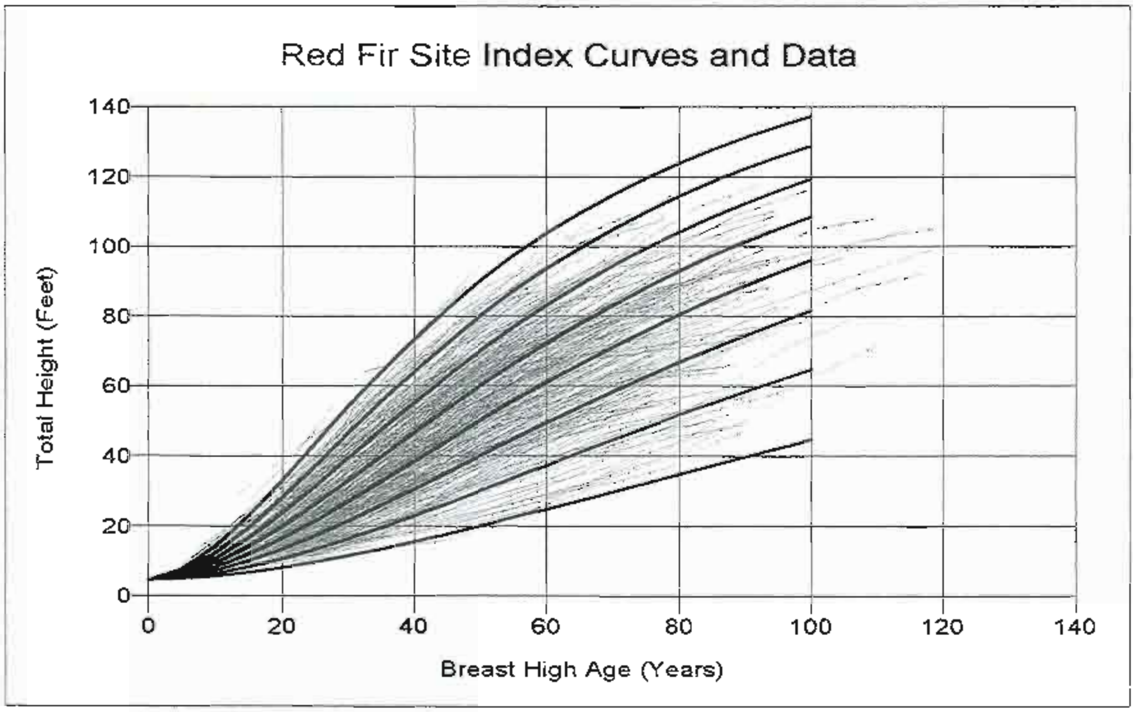

Figure I.22. *Red fir height growth data used in model construction.*

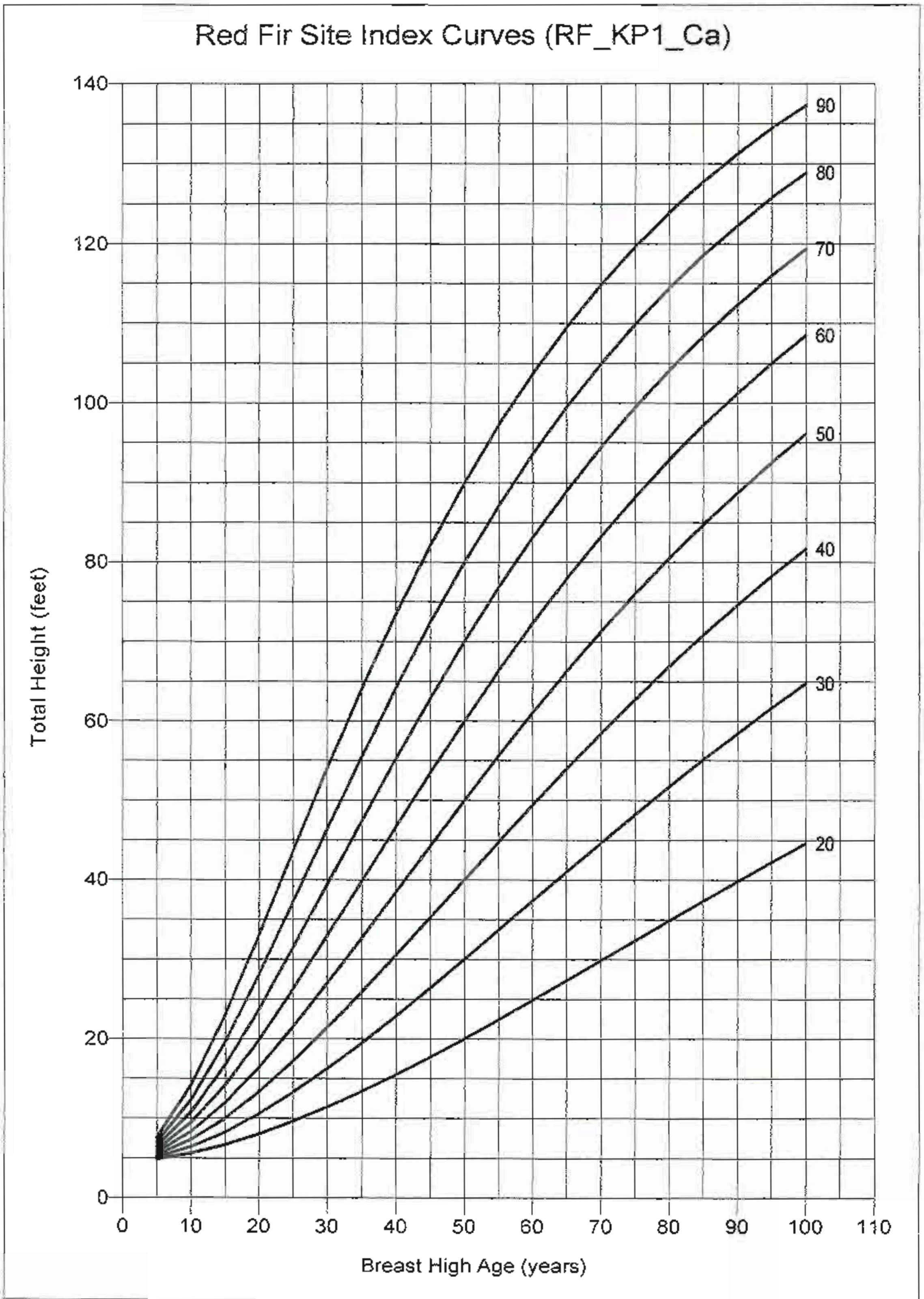

Figure I.23. *Red fir site index curves for the RF_KP1_Ca model .*

Table I.8. Red fir site index table for the RF_KP1_Ca model.

Red Fir Site Index Table (RF_KP1_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index														
Age	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
12	6.0	6.5	7.0	7.6	8.2	8.9	9.6	10.4	11.2	12.0	13.0	14.0	15.0	16.2	17.5
14	6.4	7.1	7.8	8.6	9.4	10.2	11.1	12.1	13.1	14.2	15.4	16.7	18.0	19.5	21.1
16	6.9	7.7	8.6	9.6	10.6	11.6	12.8	14.0	15.2	16.6	18.0	19.6	21.2	23.0	24.9
18	7.4	8.5	9.5	10.7	11.9	13.2	14.5	16.0	17.5	19.1	20.8	22.6	24.6	26.7	28.9
20	8.0	9.2	10.5	11.9	13.3	14.8	16.4	18.1	19.9	21.7	23.7	25.8	28.1	30.5	33.0
22	8.6	10.0	11.6	13.1	14.8	16.5	18.4	20.3	22.3	24.5	26.7	29.1	31.7	34.4	37.2
24	9.2	10.9	12.6	14.5	16.4	18.3	20.4	22.6	24.9	27.3	29.8	32.5	35.3	38.3	41.4
26	9.9	11.8	13.8	15.8	18.0	20.2	22.5	25.0	27.5	30.2	33.0	35.9	39.0	42.2	45.7
28	10.6	12.8	15.0	17.3	19.6	22.1	24.7	27.4	30.2	33.1	36.2	39.3	42.7	46.2	49.8
30	11.4	13.7	16.2	18.7	21.4	24.1	26.9	29.9	32.9	36.1	39.4	42.8	46.4	50.1	54.0
32	12.1	14.8	17.5	20.3	23.1	26.1	29.2	32.4	35.6	39.1	42.6	46.2	50.0	54.0	58.0
34	12.9	15.8	18.8	21.8	24.9	28.2	31.5	34.9	38.4	42.0	45.8	49.7	53.6	57.8	62.0
36	13.8	16.9	20.1	23.4	26.8	30.2	33.8	37.4	41.2	45.0	49.0	53.0	57.2	61.5	65.9
38	14.6	18.0	21.5	25.0	28.6	32.3	36.1	40.0	43.9	48.0	52.1	56.4	60.7	65.2	69.7
40	15.4	19.1	22.8	26.6	30.5	34.4	38.4	42.5	46.7	50.9	55.2	59.6	64.1	68.7	73.4
42	16.3	20.3	24.2	28.3	32.4	36.5	40.8	45.1	49.4	53.8	58.3	62.9	67.5	72.2	77.0
44	17.2	21.4	25.7	29.9	34.3	38.7	43.1	47.6	52.1	56.7	61.3	66.0	70.7	75.5	80.4
46	18.1	22.6	27.1	31.6	36.2	40.8	45.4	50.1	54.8	59.5	64.3	69.1	73.9	78.8	83.7
48	19.1	23.8	28.5	33.3	38.1	42.9	47.7	52.6	57.4	62.3	67.2	72.1	77.0	82.0	86.9
50	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0
52	21.0	26.2	31.5	36.7	41.9	47.1	52.3	57.4	62.5	67.7	72.8	77.8	82.9	87.9	93.0
54	21.9	27.4	32.9	38.4	43.8	49.2	54.5	59.8	65.1	70.3	75.5	80.6	85.7	90.8	95.8
56	22.9	28.7	34.4	40.1	45.7	51.2	56.7	62.1	67.5	72.8	78.1	83.3	88.4	93.5	98.6
58	23.9	29.9	35.9	41.8	47.6	53.3	58.9	64.4	69.9	75.3	80.6	85.9	91.0	96.1	101.2
60	24.8	31.2	37.4	43.4	49.4	55.3	61.0	66.7	72.3	77.7	83.1	88.4	93.6	98.7	103.7
62	25.8	32.4	38.8	45.1	51.3	57.3	63.2	68.9	74.6	80.1	85.5	90.8	96.0	101.1	106.1
64	26.8	33.6	40.3	46.8	53.1	59.2	65.2	71.1	76.8	82.4	87.8	93.2	98.4	103.5	108.4
66	27.8	34.9	41.7	48.4	54.9	61.2	67.3	73.2	79.0	84.6	90.1	95.5	100.7	105.7	110.7
68	28.8	36.1	43.2	50.0	56.7	63.1	69.3	75.3	81.1	86.8	92.3	97.7	102.8	107.9	112.8
70	29.8	37.4	44.6	51.7	58.4	64.9	71.2	77.3	83.2	88.9	94.4	99.8	105.0	110.0	114.8
72	30.8	38.6	46.1	53.3	60.1	66.8	73.2	79.3	85.3	91.0	96.5	101.8	107.0	112.0	116.8
74	31.8	39.8	47.5	54.8	61.9	68.6	75.1	81.3	87.2	93.0	98.5	103.8	109.0	113.9	118.7
76	32.8	41.1	48.9	56.4	63.5	70.4	76.9	83.2	89.2	94.9	100.4	105.7	110.8	115.8	120.5
78	33.8	42.3	50.3	57.9	65.2	72.1	78.7	85.0	91.0	96.8	102.3	107.6	112.7	117.5	122.2
80	34.8	43.5	51.7	59.5	66.8	73.8	80.5	86.8	92.9	98.6	104.1	109.4	114.4	119.3	123.9
82	35.8	44.7	53.1	61.0	68.4	75.5	82.2	88.6	94.6	100.4	105.9	111.1	116.1	120.9	125.5
84	36.8	45.9	54.4	62.5	70.0	77.2	83.9	90.3	96.3	102.1	107.6	112.8	117.7	122.5	127.0
86	37.8	47.1	55.8	63.9	71.6	78.8	85.6	92.0	98.0	103.8	109.2	114.4	119.3	124.0	128.5
88	38.8	48.3	57.1	65.4	73.1	80.3	87.2	93.6	99.7	105.4	110.8	115.9	120.8	125.5	129.9
90	39.8	49.5	58.4	66.8	74.6	81.9	88.7	95.2	101.2	106.9	112.3	117.4	122.3	126.9	131.2
92	40.8	50.6	59.7	68.2	76.1	83.4	90.3	96.7	102.8	108.5	113.8	118.9	123.7	128.2	132.5
94	41.7	51.8	61.0	69.6	77.5	84.9	91.8	98.2	104.3	109.9	115.3	120.3	125.0	129.5	133.8
96	42.7	52.9	62.3	70.9	78.9	86.3	93.2	99.7	105.7	111.4	116.7	121.7	126.4	130.8	135.0
98	43.7	54.0	63.5	72.2	80.3	87.8	94.7	101.1	107.1	112.7	118.0	123.0	127.6	132.0	136.1
100	44.6	55.1	64.7	73.6	81.7	89.1	96.1	102.5	108.5	114.1	119.3	124.2	128.8	133.2	137.3

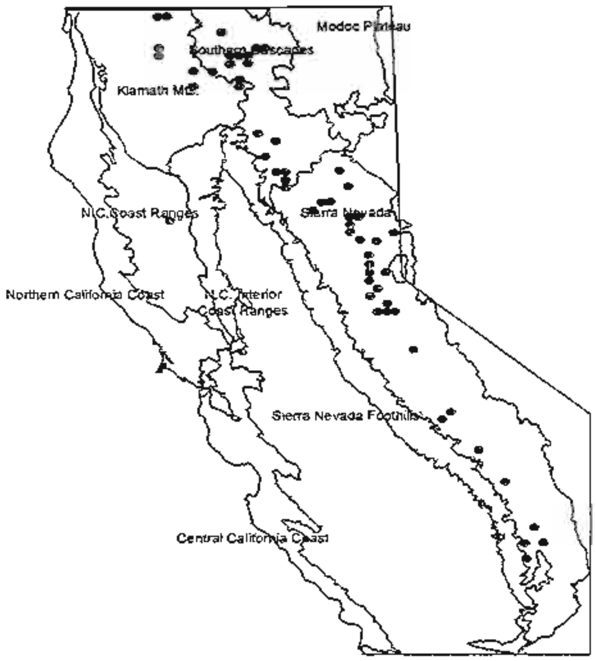

Figure I.24. *Sample locations of red fir in California used in modeling.*

I.2.9 Incense-Cedar

Model Name: IC_LG1_Ca
Model Form: LG1

Synopsis

The incense-cedar site index model IC_LG1_Ca is applicable to incense-cedar anywhere it is found in California. The applicable age range is nominally 10 – 100 years and the site index range is 20 - 90 feet. While being a common mixed-conifer component, incense-cedar is in a class of its own with site index values being typically ~30% lower than MC3 species and white fir.

Figure I.25 shows the time series data used in fitting the model. Figure I.26 shows site curve graphs. Table I.9 provides tabular values of heights by breast-high age and site index. Figure I.27 maps the statewide incense-cedar sampling locations.

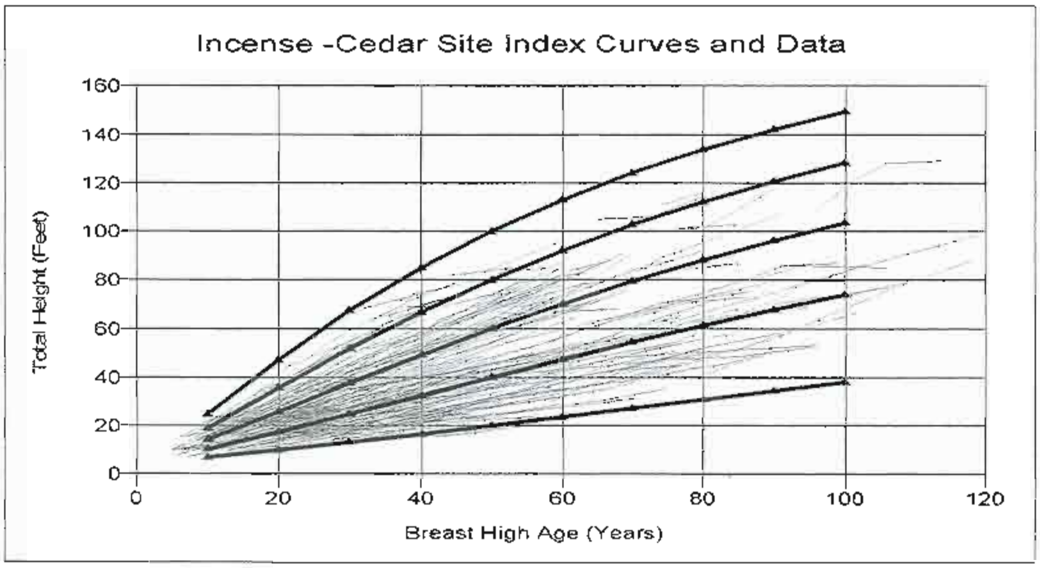

Figure 1.25. *Incense-cedar height growth data used in model construction.*

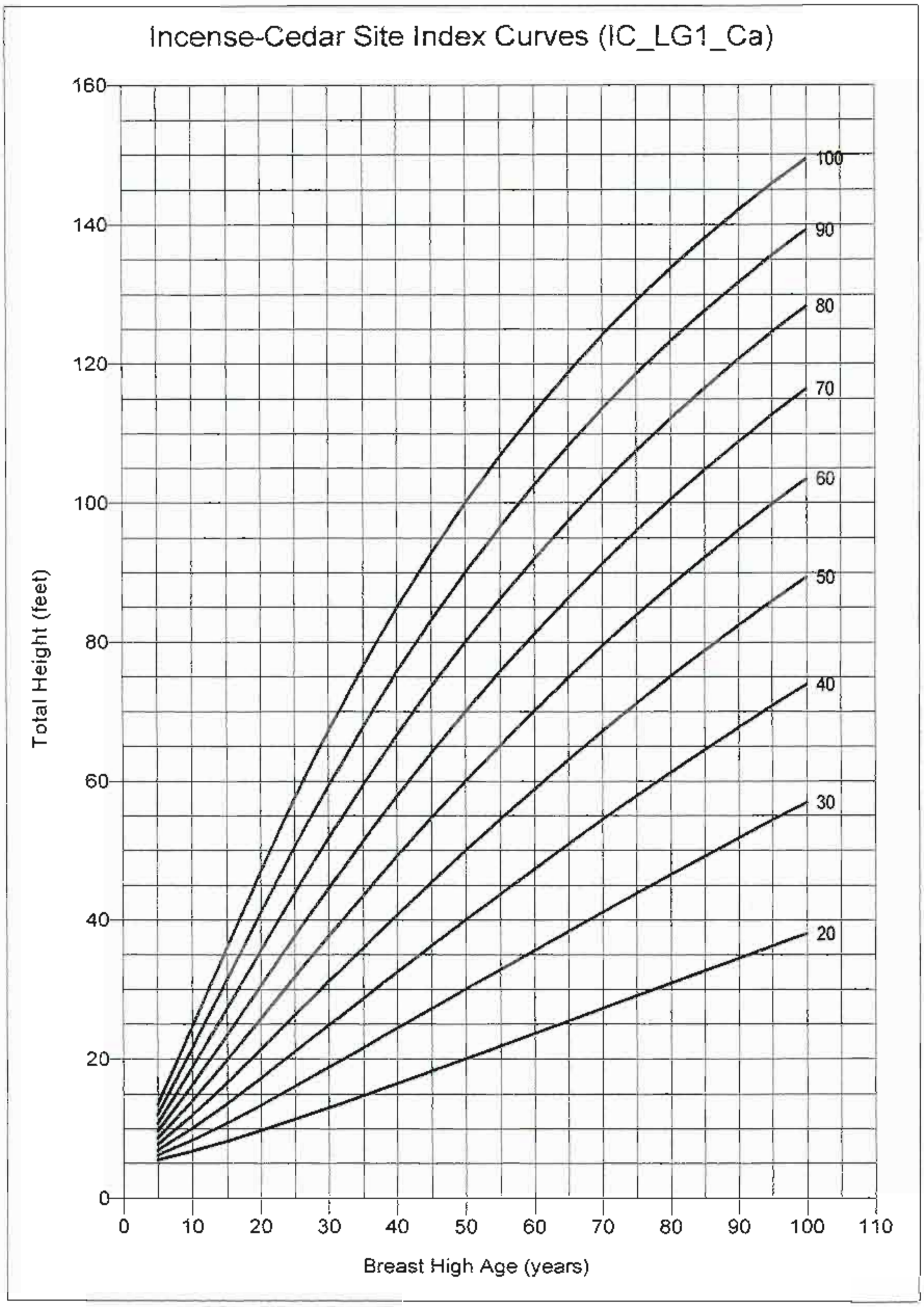

Figure I.26. *Incense-cedar site index curves for the IC_LG1_Ca model.*

Table I.9. Incense-cedar site index tables for the IC_LG1_Ca model.

Incense-cedar Site Index Table (IC_LG1_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index																
Age	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
12	7.3	8.3	9.3	10.4	11.5	12.6	13.8	15.0	16.3	17.7	19.1	20.6	22.1	23.8	25.5	27.3	29.2
14	7.9	9.1	10.3	11.5	12.9	14.2	15.6	17.1	18.7	20.3	21.9	23.7	25.5	27.4	29.4	31.5	33.7
16	8.5	9.9	11.3	12.8	14.3	15.9	17.5	19.2	21.0	22.9	24.8	26.8	28.9	31.1	33.4	35.7	38.2
18	9.1	10.7	12.3	14.0	15.8	17.6	19.4	21.4	23.4	25.5	27.7	29.9	32.3	34.7	37.2	39.9	42.7
20	9.7	11.5	13.4	15.3	17.2	19.3	21.4	23.5	25.8	28.1	30.5	33.0	35.6	38.3	41.1	44.0	47.0
22	10.4	12.4	14.4	16.6	18.7	21.0	23.3	25.7	28.2	30.7	33.4	36.1	38.9	41.9	44.9	48.0	51.3
24	11.0	13.2	15.5	17.8	20.3	22.7	25.3	27.9	30.6	33.4	36.2	39.2	42.2	45.4	48.6	52.0	55.4
26	11.7	14.1	16.6	19.1	21.8	24.5	27.2	30.1	33.0	36.0	39.0	42.2	45.4	48.8	52.3	55.8	59.5
28	12.3	15.0	17.7	20.5	23.3	26.2	29.2	32.2	35.3	38.5	41.8	45.2	48.6	52.2	55.8	59.6	63.4
30	13.0	15.9	18.8	21.8	24.8	27.9	31.1	34.4	37.7	41.1	44.6	48.1	51.8	55.5	59.3	63.3	67.3
32	13.7	16.8	19.9	23.1	26.4	29.7	33.0	36.5	40.0	43.6	47.3	51.0	54.9	58.8	62.8	66.8	71.0
34	14.4	17.7	21.0	24.4	27.9	31.4	35.0	38.6	42.3	46.1	50.0	53.9	57.9	62.0	66.1	70.3	74.6
36	15.1	18.6	22.1	25.7	29.4	33.1	36.9	40.8	44.6	48.6	52.6	56.7	60.9	65.1	69.4	73.7	78.1
38	15.8	19.5	23.3	27.1	30.9	34.9	38.8	42.9	46.9	51.1	55.2	59.5	63.8	68.1	72.6	77.0	81.6
40	16.5	20.4	24.4	28.4	32.5	36.6	40.7	44.9	49.2	53.5	57.8	62.2	66.6	71.1	75.7	80.2	84.9
42	17.2	21.3	25.5	29.7	34.0	38.3	42.6	47.0	51.4	55.8	60.3	64.8	69.4	74.0	78.7	83.4	88.1
44	17.9	22.2	26.6	31.1	35.5	40.0	44.5	49.0	53.6	58.2	62.8	67.5	72.1	76.9	81.6	86.4	91.2
46	18.6	23.2	27.8	32.4	37.0	41.7	46.3	51.0	55.7	60.5	65.3	70.0	74.8	79.7	84.5	89.3	94.2
48	19.3	24.1	28.9	33.7	38.5	43.3	48.2	53.0	57.9	62.8	67.7	72.5	77.4	82.4	87.3	92.2	97.2
50	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0
52	20.7	25.9	31.1	36.3	41.5	46.7	51.8	57.0	62.1	67.2	72.3	77.4	82.5	87.6	92.7	97.7	102.7
54	21.5	26.9	32.3	37.6	43.0	48.3	53.6	58.9	64.1	69.4	74.6	79.8	84.9	90.1	95.2	100.3	105.4
56	22.2	27.8	33.4	38.9	44.4	49.9	55.4	60.8	66.1	71.5	76.8	82.1	87.3	92.6	97.8	102.9	108.0
58	22.9	28.7	34.5	40.2	45.9	51.5	57.1	62.7	68.1	73.6	79.0	84.3	89.7	95.0	100.2	105.4	110.5
60	23.6	29.6	35.6	41.5	47.4	53.1	58.8	64.5	70.1	75.7	81.2	86.6	92.0	97.3	102.6	107.8	113.0
62	24.3	30.6	36.7	42.8	48.8	54.7	60.5	66.3	72.0	77.7	83.3	88.7	94.2	99.6	104.9	110.1	115.3
64	25.1	31.5	37.8	44.1	50.2	56.3	62.2	68.1	73.9	79.7	85.3	90.9	96.4	101.8	107.2	112.4	117.6
66	25.8	32.4	38.9	45.3	51.6	57.8	63.9	69.9	75.8	81.6	87.4	93.0	98.5	104.0	109.4	114.6	119.8
68	26.5	33.3	40.0	46.6	53.0	59.4	65.6	71.7	77.7	83.5	89.3	95.0	100.6	106.1	111.5	116.8	122.0
70	27.2	34.3	41.1	47.8	54.4	60.9	67.2	73.4	79.5	85.4	91.3	97.0	102.6	108.2	113.6	118.9	124.1
72	28.0	35.2	42.2	49.1	55.8	62.4	68.8	75.1	81.3	87.3	93.2	98.9	104.6	110.2	115.6	120.9	126.1
74	28.7	36.1	43.3	50.3	57.2	63.9	70.4	76.8	83.0	89.1	95.1	100.9	106.6	112.1	117.6	122.9	128.1
76	29.4	37.0	44.4	51.5	58.5	65.4	72.0	78.4	84.7	90.9	96.9	102.7	108.5	114.1	119.5	124.8	130.0
78	30.2	37.9	45.5	52.8	59.9	66.8	73.5	80.1	86.4	92.7	98.7	104.6	110.3	115.9	121.4	126.7	131.9
80	30.9	38.8	46.5	54.0	61.2	68.3	75.1	81.7	88.1	94.4	100.5	106.4	112.1	117.8	123.2	128.5	133.7
82	31.6	39.7	47.6	55.2	62.5	69.7	76.6	83.3	89.8	96.1	102.2	108.1	113.9	119.5	125.0	130.3	135.5
84	32.3	40.6	48.6	56.4	63.9	71.1	78.1	84.8	91.4	97.8	103.9	109.9	115.7	121.3	126.8	132.1	137.2
86	33.0	41.5	49.7	57.6	65.2	72.5	79.5	86.4	93.0	99.4	105.6	111.5	117.4	123.0	128.5	133.7	138.9
88	33.8	42.4	50.7	58.7	66.4	73.9	81.0	87.9	94.6	101.0	107.2	113.2	119.0	124.7	130.1	135.4	140.5
90	34.5	43.3	51.8	59.9	67.7	75.2	82.4	89.4	96.1	102.6	108.8	114.8	120.6	126.3	131.7	137.0	142.1
92	35.2	44.2	52.8	61.1	69.0	76.6	83.9	90.9	97.6	104.1	110.4	116.4	122.2	127.9	133.3	138.5	143.6
94	35.9	45.1	53.8	62.2	70.2	77.9	85.3	92.3	99.1	105.7	111.9	118.0	123.8	129.4	134.8	140.1	145.1
96	36.6	46.0	54.9	63.3	71.5	79.2	86.6	93.8	100.6	107.2	113.5	119.5	125.3	130.9	136.3	141.5	146.6
98	37.3	46.8	55.9	64.5	72.7	80.5	88.0	95.2	102.0	108.6	114.9	121.0	126.8	132.4	137.8	143.0	148.0
100	38.1	47.7	56.9	65.6	73.9	81.8	89.3	96.6	103.5	110.1	116.4	122.4	128.3	133.9	139.2	144.4	149.4

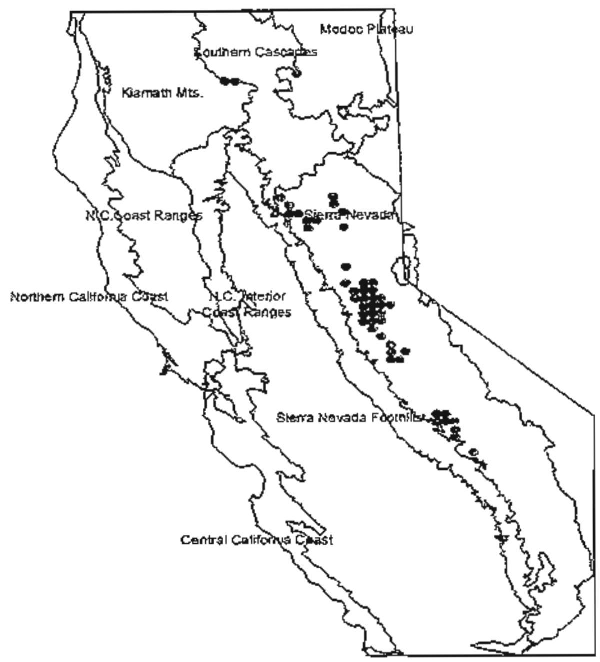

Figure I.27. *Incense-cedar sampling locations in California.*

I.2.10 Jeffrey Pine and Lodgepole Pine

Model Name: JP_SH2_Ca
Model Form: SH2

Synopsis

Lodgepole pine site curves were found to be almost coincident with those of Jeffrey pine so the JP_SH2_Ca model was considered to be applicable to both species. For Jeffrey pine, the age range of the data is 10 – 120 years and the site index range is 20 – 80 feet. Lodgepole pine had a similar age range but the site range was about 30 – 60 feet.

Figure I.28 shows site curve graphs for the JP_SH2_Ca model. Table I.10 provides tabular values of heights by breast-high age and site index. Table 1.11 and table I.12 provides the number of sampling locations by county for Jeffrey pine and lodgepole pine respectively.

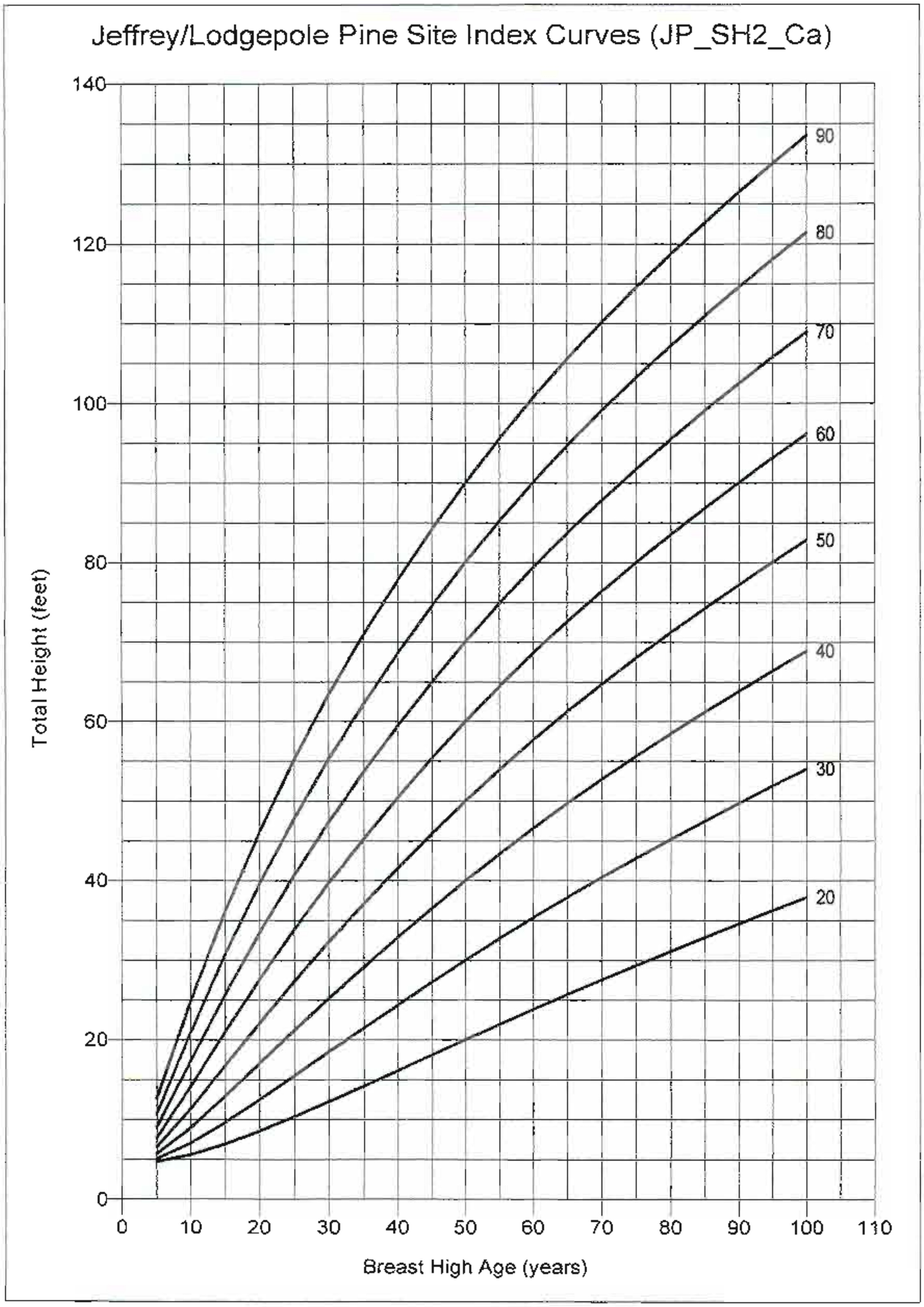

Figure I.28. *Jeffrey/Lodgepole pine site index curves for the JP_SH2_Ca model.*

Table I.10. Jeffrey/Lodgepole pine site index table for the JP_SH2_Ca model.

Jeffrey/Lodgepole Pine Site Index Table (JP_SH2_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index														
Age	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
12	6.0	6.9	8.0	9.2	10.5	11.9	13.4	15.1	16.9	18.7	20.7	22.7	24.9	27.1	29.5
14	6.6	7.7	9.0	10.5	12.1	13.8	15.6	17.5	19.6	21.7	24.0	26.3	28.8	31.3	33.9
16	7.2	8.6	10.2	11.9	13.7	15.7	17.8	20.0	22.3	24.7	27.2	29.8	32.5	35.3	38.2
18	7.9	9.5	11.3	13.3	15.4	17.6	19.9	22.4	25.0	27.6	30.4	33.2	36.1	39.2	42.2
20	8.5	10.4	12.5	14.7	17.0	19.5	22.1	24.8	27.6	30.5	33.4	36.5	39.6	42.8	46.1
22	9.2	11.4	13.7	16.1	18.7	21.4	24.2	27.1	30.1	33.2	36.4	39.7	43.0	46.4	49.9
24	10.0	12.3	14.9	17.5	20.3	23.3	26.3	29.4	32.6	35.9	39.3	42.7	46.2	49.8	53.5
26	10.7	13.3	16.1	19.0	22.0	25.1	28.3	31.6	35.0	38.5	42.1	45.7	49.4	53.1	56.9
28	11.5	14.3	17.3	20.4	23.6	26.9	30.3	33.8	37.4	41.1	44.8	48.5	52.4	56.3	60.2
30	12.2	15.3	18.5	21.8	25.2	28.7	32.3	36.0	39.7	43.5	47.4	51.3	55.3	59.3	63.4
32	13.0	16.3	19.7	23.2	26.8	30.5	34.2	38.1	42.0	45.9	49.9	54.0	58.1	62.3	66.5
34	13.8	17.2	20.8	24.5	28.3	32.2	36.1	40.1	44.2	48.3	52.4	56.6	60.8	65.1	69.4
36	14.5	18.2	22.0	25.9	29.9	33.9	38.0	42.1	46.3	50.5	54.8	59.1	63.5	67.9	72.3
38	15.3	19.2	23.2	27.3	31.4	35.6	39.8	44.1	48.4	52.8	57.2	61.6	66.1	70.5	75.1
40	16.1	20.2	24.4	28.6	32.9	37.2	41.6	46.0	50.5	54.9	59.4	64.0	68.5	73.1	77.7
42	16.9	21.2	25.5	29.9	34.3	38.8	43.3	47.9	52.4	57.0	61.7	66.3	71.0	75.6	80.3
44	17.7	22.1	26.6	31.2	35.8	40.4	45.0	49.7	54.4	59.1	63.8	68.6	73.3	78.1	82.9
46	18.4	23.1	27.8	32.5	37.2	42.0	46.7	51.5	56.3	61.1	65.9	70.8	75.6	80.5	85.3
48	19.2	24.1	28.9	33.8	38.6	43.5	48.4	53.3	58.2	63.1	68.0	72.9	77.8	82.8	87.7
50	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0
52	20.8	25.9	31.1	36.2	41.4	46.5	51.6	56.7	61.8	66.9	72.0	77.0	82.1	87.2	92.3
54	21.5	26.9	32.2	37.5	42.7	47.9	53.2	58.4	63.5	68.7	73.9	79.0	84.2	89.3	94.4
56	22.3	27.8	33.2	38.7	44.0	49.4	54.7	60.0	65.3	70.5	75.8	81.0	86.2	91.4	96.6
58	23.1	28.7	34.3	39.8	45.3	50.8	56.2	61.6	66.9	72.3	77.6	82.9	88.2	93.4	98.7
60	23.8	29.6	35.4	41.0	46.6	52.2	57.7	63.1	68.6	74.0	79.4	84.7	90.1	95.4	100.7
62	24.6	30.5	36.4	42.2	47.9	53.5	59.1	64.7	70.2	75.7	81.1	86.6	92.0	97.3	102.7
64	25.3	31.4	37.4	43.3	49.1	54.9	60.6	66.2	71.8	77.3	82.9	88.3	93.8	99.2	104.6
66	26.1	32.3	38.4	44.4	50.3	56.2	62.0	67.7	73.3	79.0	84.5	90.1	95.6	101.1	106.5
68	26.8	33.2	39.4	45.5	51.6	57.5	63.3	69.1	74.9	80.6	86.2	91.8	97.4	102.9	108.4
70	27.5	34.1	40.4	46.6	52.7	58.8	64.7	70.6	76.4	82.1	87.8	93.5	99.1	104.6	110.2
72	28.3	34.9	41.4	47.7	53.9	60.0	66.0	72.0	77.8	83.7	89.4	95.1	100.8	106.4	111.9
74	29.0	35.8	42.4	48.8	55.1	61.3	67.4	73.4	79.3	85.2	91.0	96.7	102.4	108.1	113.7
76	29.7	36.6	43.3	49.8	56.2	62.5	68.7	74.7	80.7	86.6	92.5	98.3	104.0	109.7	115.4
78	30.4	37.5	44.3	50.9	57.4	63.7	69.9	76.1	82.1	88.1	94.0	99.8	105.6	111.4	117.1
80	31.1	38.3	45.2	51.9	58.5	64.9	71.2	77.4	83.5	89.5	95.5	101.4	107.2	113.0	118.7
82	31.8	39.1	46.1	52.9	59.6	66.1	72.4	78.7	84.9	90.9	96.9	102.9	108.7	114.5	120.3
84	32.5	39.9	47.0	53.9	60.7	67.2	73.6	80.0	86.2	92.3	98.4	104.3	110.2	116.1	121.9
86	33.2	40.7	48.0	54.9	61.7	68.4	74.9	81.2	87.5	93.7	99.8	105.8	111.7	117.6	123.4
88	33.9	41.5	48.9	55.9	62.8	69.5	76.0	82.5	88.8	95.0	101.1	107.2	113.2	119.1	124.9
90	34.6	42.3	49.7	56.9	63.8	70.6	77.2	83.7	90.1	96.3	102.5	108.6	114.6	120.5	126.4
92	35.3	43.1	50.6	57.9	64.9	71.7	78.4	84.9	91.3	97.6	103.8	110.0	116.0	122.0	127.9
94	35.9	43.9	51.5	58.8	65.9	72.8	79.5	86.1	92.5	98.9	105.1	111.3	117.4	123.4	129.3
96	36.6	44.7	52.4	59.7	66.9	73.8	80.6	87.3	93.8	100.2	106.4	112.6	118.7	124.8	130.7
98	37.3	45.4	53.2	60.7	67.9	74.9	81.7	88.4	95.0	101.4	107.7	113.9	120.1	126.1	132.1
100	37.9	46.2	54.1	61.6	68.9	75.9	82.8	89.6	96.1	102.6	109.0	115.2	121.4	127.5	133.5

Table I.11. Numbers of Jeffrey pine sampling locations by county.

County	Numbers of Stands
Alpine	3
Amador	2
El Dorado	1
Inyo	1
Kern	2
Lassen	10
Modoc	3
Nevada	2
Placer	3
Plumas	5
San Bernardino	1
Sierra	1
Siskiyou	3
Tehama	1
Trinity	1
Tuolumne	1

Table I.12. Numbers of lodgepole pine sampling locations by county

County	Numbers of Stands
Amador	1
Butte	1
El Dorado	1
Inyo	1
Lassen	1
Modoc	1
Nevada	1
Placer	1
Sierra	1
Siskiyou	5

I.3 Hardwood Site index Models

I.3.1 Red Alder

Model Name: RA_SH1_Ca
Model Form: SH1

Synopsis

The red alder site index model *RA_SH1_Ca* is applicable to red alder in the North Coast region of California. The data used in fitting the site index model was confined to the redwood zone in Humboldt, Del Norte, and Mendocino counties. The approximate breast-high age range of the data 10 – 60 years and the site index range is 40 - 110 feet.

Figure I.29 shows site curve graphs for the *RA_SH1_Ca* model. Table 1.13 provides the number of sampling locations by county for red alder. Table I.14 provides tabular values of heights by breast-high age and site index.

County	Numbers of Stands
Del Norte	3
Mendocino	3
Humboldt	6

Table I.13. Numbers of red alder sampling locations by county.

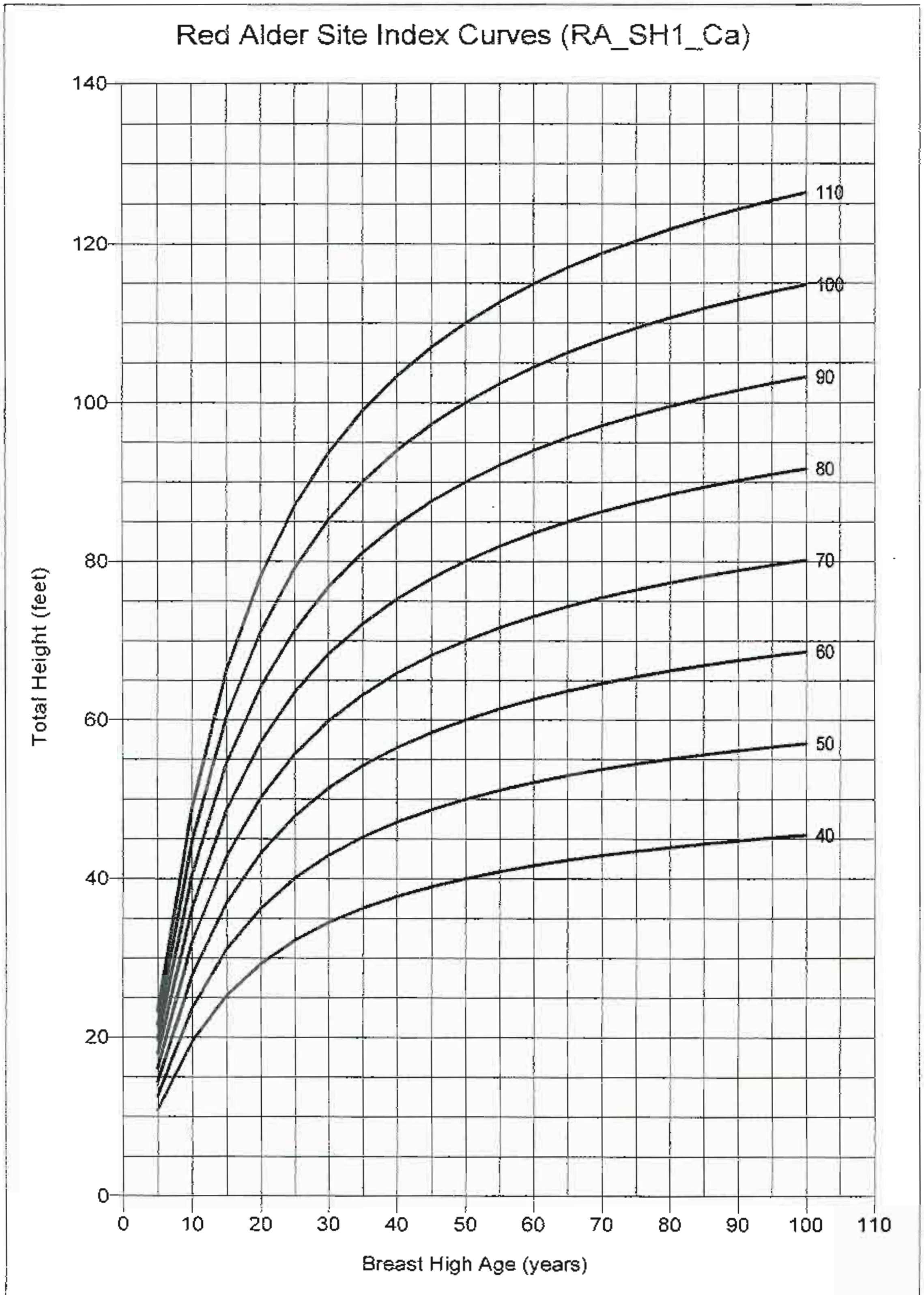

Figure I.29. *Red alder site index curves for the RA_SH1_Ca model.*

Table I.14. Red alder site index table for the RA_SH1_Ca model.

Red Alder Site Index Table (RA_SH1_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index														
Age	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110
12	22.1	24.6	27.0	29.5	32.0	34.5	36.9	39.4	41.9	44.4	46.8	49.3	51.8	54.3	56.7
14	24.3	27.1	29.9	32.6	35.4	38.2	41.0	43.8	46.6	49.4	52.2	54.9	57.7	60.5	63.3
16	26.2	29.2	32.3	35.4	38.4	41.5	44.5	47.6	50.6	53.7	56.7	59.8	62.8	65.9	69.0
18	27.8	31.1	34.4	37.7	41.0	44.3	47.6	50.8	54.1	57.4	60.7	64.0	67.3	70.6	73.9
20	29.3	32.8	36.3	39.8	43.2	46.7	50.2	53.7	57.2	60.7	64.2	67.7	71.2	74.7	78.2
22	30.6	34.2	37.9	41.6	45.3	48.9	52.6	56.3	59.9	63.6	67.3	70.9	74.6	78.3	82.0
24	31.7	35.5	39.4	43.2	47.0	50.9	54.7	58.5	62.4	66.2	70.0	73.9	77.7	81.5	85.4
26	32.7	36.7	40.7	44.7	48.6	52.6	56.6	60.6	64.5	68.5	72.5	76.5	80.4	84.4	88.4
28	33.7	37.8	41.9	46.0	50.1	54.2	58.3	62.4	66.5	70.6	74.7	78.8	82.9	87.0	91.1
30	34.5	38.7	42.9	47.2	51.4	55.6	59.8	64.1	68.3	72.5	76.7	81.0	85.2	89.4	93.6
32	35.3	39.6	43.9	48.3	52.6	56.9	61.2	65.6	69.9	74.2	78.6	82.9	87.2	91.6	95.9
34	36.0	40.4	44.8	49.2	53.7	58.1	62.5	67.0	71.4	75.8	80.3	84.7	89.1	93.6	98.0
36	36.6	41.1	45.6	50.2	54.7	59.2	63.7	68.3	72.8	77.3	81.8	86.3	90.9	95.4	99.9
38	37.2	41.8	46.4	51.0	55.6	60.2	64.8	69.4	74.0	78.6	83.2	87.9	92.5	97.1	101.7
40	37.7	42.4	47.1	51.8	56.5	61.2	65.8	70.5	75.2	79.9	84.6	89.3	93.9	98.6	103.3
42	38.3	43.0	47.8	52.5	57.3	62.0	66.8	71.5	76.3	81.1	85.8	90.6	95.3	100.1	104.8
44	38.7	43.6	48.4	53.2	58.0	62.9	67.7	72.5	77.3	82.1	87.0	91.8	96.6	101.4	106.3
46	39.2	44.1	49.0	53.8	58.7	63.6	68.5	73.4	78.3	83.2	88.0	92.9	97.8	102.7	107.6
48	39.6	44.6	49.5	54.4	59.4	64.3	69.3	74.2	79.2	84.1	89.1	94.0	98.9	103.9	108.8
50	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0
52	40.4	45.4	50.5	55.5	60.6	65.6	70.7	75.7	80.8	85.8	90.9	95.9	101.0	106.0	111.1
54	40.7	45.8	50.9	56.0	61.1	66.2	71.3	76.4	81.5	86.6	91.7	96.8	101.9	107.0	112.1
56	41.1	46.2	51.3	56.5	61.6	66.8	71.9	77.1	82.2	87.4	92.5	97.7	102.8	108.0	113.1
58	41.4	46.6	51.7	56.9	62.1	67.3	72.5	77.7	82.9	88.1	93.3	98.5	103.7	108.9	114.1
60	41.7	46.9	52.1	57.4	62.6	67.8	73.1	78.3	83.5	88.8	94.0	99.2	104.5	109.7	114.9
62	41.9	47.2	52.5	57.8	63.0	68.3	73.6	78.9	84.1	89.4	94.7	100.0	105.2	110.5	115.8
64	42.2	47.5	52.8	58.1	63.5	68.8	74.1	79.4	84.7	90.0	95.3	100.6	105.9	111.3	116.6
66	42.5	47.8	53.2	58.5	63.9	69.2	74.5	79.9	85.2	90.6	95.9	101.3	106.6	112.0	117.3
68	42.7	48.1	53.5	58.9	64.2	69.6	75.0	80.4	85.8	91.1	96.5	101.9	107.3	112.7	118.1
70	42.9	48.4	53.8	59.2	64.6	70.0	75.4	80.8	86.3	91.7	97.1	102.5	107.9	113.3	118.7
72	43.2	48.6	54.1	59.5	64.9	70.4	75.8	81.3	86.7	92.2	97.6	103.1	108.5	114.0	119.4
74	43.4	48.9	54.3	59.8	65.3	70.8	76.2	81.7	87.2	92.7	98.1	103.6	109.1	114.6	120.0
76	43.6	49.1	54.6	60.1	65.6	71.1	76.6	82.1	87.6	93.1	98.6	104.1	109.6	115.1	120.6
78	43.8	49.3	54.8	60.4	65.9	71.4	77.0	82.5	88.0	93.6	99.1	104.6	110.2	115.7	121.2
80	44.0	49.5	55.1	60.6	66.2	71.8	77.3	82.9	88.4	94.0	99.5	105.1	110.7	116.2	121.8
82	44.1	49.7	55.3	60.9	66.5	72.1	77.6	83.2	88.8	94.4	100.0	105.6	111.2	116.7	122.3
84	44.3	49.9	55.5	61.1	66.8	72.4	78.0	83.6	89.2	94.8	100.4	106.0	111.6	117.2	122.8
86	44.5	50.1	55.7	61.4	67.0	72.6	78.3	83.9	89.5	95.2	100.8	106.4	112.1	117.7	123.3
88	44.6	50.3	56.0	61.6	67.3	72.9	78.6	84.2	89.9	95.5	101.2	106.8	112.5	118.2	123.8
90	44.8	50.5	56.2	61.8	67.5	73.2	78.9	84.5	90.2	95.9	101.6	107.2	112.9	118.6	124.3
92	45.0	50.6	56.3	62.0	67.7	73.4	79.1	84.8	90.5	96.2	101.9	107.6	113.3	119.0	124.7
94	45.1	50.8	56.5	62.3	68.0	73.7	79.4	85.1	90.8	96.6	102.3	108.0	113.7	119.4	125.1
96	45.2	51.0	56.7	62.4	68.2	73.9	79.7	85.4	91.1	96.9	102.6	108.3	114.1	119.8	125.6
98	45.4	51.1	56.9	62.6	68.4	74.2	79.9	85.7	91.4	97.2	102.9	108.7	114.5	120.2	126.0
100	45.5	51.3	57.1	62.8	68.6	74.4	80.2	85.9	91.7	97.5	103.3	109.0	114.8	120.6	126.4

I.3.2 Madrone

Model Name: MD_SH1_Ca
Model Form: SH1

Synopsis

The madrone site index model MD_*SH1_Ca* is applicable to madrone in the North Coast region of California and in the interior. The data used in fitting the site index model was primarily from the redwood zone in Humboldt and Mendocino counties. The approximate breast-high age range of the data 10 – 100 years and the site index range is 30 - 80 feet.

Figure I.30 shows site curve graphs for the MD_*SH1_Ca* model. Table I.15 provides the number of sampling locations by county for madrone. Table I.16 provides tabular values of heights by breast-high age and site index.

Table I.15. Numbers of madrone sampling locations by county.

County	Numbers of Stands
Alameda	1
Humboldt	14
Mendocino	22
Monterey	1
Napa	2
San Mateo	1
Santa Cruz	1
Sonoma	5
Trinity	3
Yuba	1

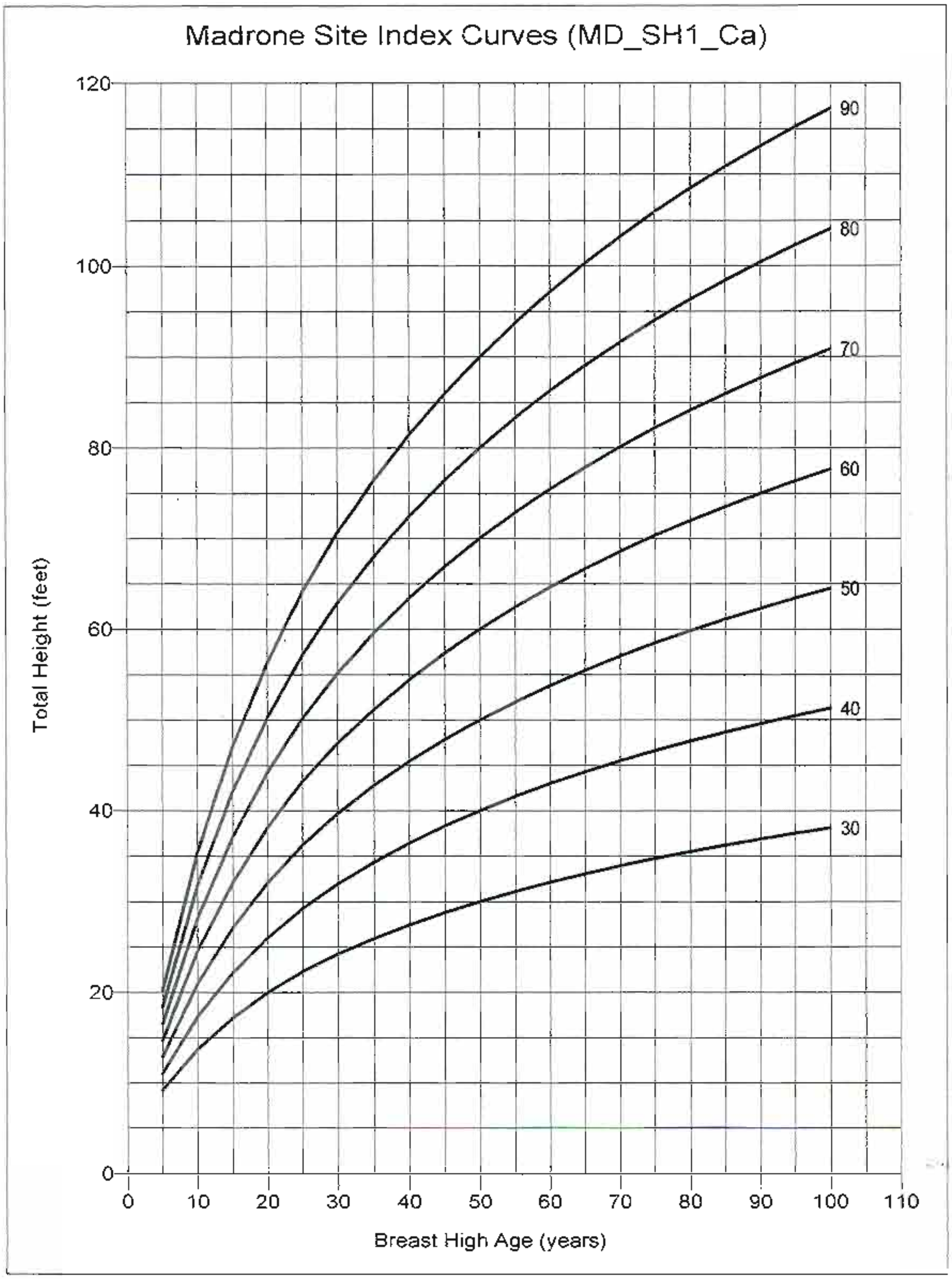

Figure I.30. *Madrone site index curves for the MD_SH1_Ca model.*

Table I.16. Madrone site index table for the MD_SH1_Ca model.

Madrone Site Index Table (MD_SH1_Ca)
Tabled values are total height in feet

BH Age	50 Year Breast-High Base Age Site Index												
	30	35	40	45	50	55	60	65	70	75	80	85	90
12	15.2	17.3	19.4	21.5	23.6	25.7	27.8	29.9	32.0	34.1	36.2	38.3	40.4
14	16.6	18.9	21.3	23.7	26.0	28.4	30.7	33.1	35.5	37.8	40.2	42.6	44.9
16	17.8	20.4	23.0	25.6	28.2	30.8	33.4	36.0	38.6	41.2	43.8	46.4	49.0
18	18.9	21.7	24.6	27.4	30.2	33.0	35.9	38.7	41.5	44.4	47.2	50.0	52.8
20	20.0	23.0	26.0	29.1	32.1	35.1	38.1	41.2	44.2	47.2	50.3	53.3	56.3
22	20.9	24.1	27.4	30.6	33.8	37.0	40.3	43.5	46.7	49.9	53.1	56.4	59.6
24	21.8	25.2	28.6	32.0	35.4	38.8	42.2	45.6	49.0	52.4	55.8	59.2	62.6
26	22.7	26.2	29.8	33.4	36.9	40.5	44.1	47.6	51.2	54.7	58.3	61.9	65.4
28	23.5	27.2	30.9	34.6	38.3	42.1	45.8	49.5	53.2	56.9	60.7	64.4	68.1
30	24.2	28.1	32.0	35.8	39.7	43.6	47.4	51.3	55.2	59.0	62.9	66.8	70.6
32	24.9	28.9	32.9	36.9	41.0	45.0	49.0	53.0	57.0	61.0	65.0	69.0	73.0
34	25.6	29.7	33.9	38.0	42.2	46.3	50.4	54.6	58.7	62.8	67.0	71.1	75.3
36	26.2	30.5	34.8	39.0	43.3	47.6	51.8	56.1	60.4	64.6	68.9	73.1	77.4
38	26.9	31.2	35.6	40.0	44.4	48.8	53.2	57.5	61.9	66.3	70.7	75.1	79.4
40	27.4	31.9	36.4	40.9	45.4	49.9	54.4	58.9	63.4	67.9	72.4	76.9	81.4
42	28.0	32.6	37.2	41.8	46.4	51.0	55.6	60.2	64.8	69.4	74.1	78.7	83.3
44	28.5	33.2	37.9	42.7	47.4	52.1	56.8	61.5	66.2	70.9	75.6	80.3	85.1
46	29.0	33.8	38.7	43.5	48.3	53.1	57.9	62.7	67.5	72.3	77.1	82.0	86.8
48	29.5	34.4	39.3	44.2	49.2	54.1	59.0	63.9	68.8	73.7	78.6	83.5	88.4
50	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0
52	30.5	35.5	40.6	45.7	50.8	55.9	61.0	66.1	71.2	76.3	81.3	86.4	91.5
54	30.9	36.1	41.2	46.4	51.6	56.8	61.9	67.1	72.3	77.5	82.6	87.8	93.0
56	31.3	36.6	41.8	47.1	52.4	57.6	62.9	68.1	73.4	78.6	83.9	89.2	94.4
58	31.7	37.1	42.4	47.7	53.1	58.4	63.8	69.1	74.4	79.8	85.1	90.5	95.8
60	32.1	37.5	43.0	48.4	53.8	59.2	64.6	70.0	75.5	80.9	86.3	91.7	97.1
62	32.5	38.0	43.5	49.0	54.5	60.0	65.5	71.0	76.4	81.9	87.4	92.9	98.4
64	32.9	38.4	44.0	49.6	55.1	60.7	66.3	71.8	77.4	83.0	88.5	94.1	99.7
66	33.2	38.9	44.5	50.2	55.8	61.4	67.1	72.7	78.3	84.0	89.6	95.2	100.9
68	33.6	39.3	45.0	50.7	56.4	62.1	67.8	73.5	79.2	84.9	90.6	96.3	102.0
70	33.9	39.7	45.5	51.2	57.0	62.8	68.6	74.3	80.1	85.9	91.6	97.4	103.2
72	34.3	40.1	45.9	51.8	57.6	63.4	69.3	75.1	81.0	86.8	92.6	98.5	104.3
74	34.6	40.5	46.4	52.3	58.2	64.1	70.0	75.9	81.8	87.7	93.6	99.5	105.4
76	34.9	40.9	46.8	52.8	58.7	64.7	70.7	76.6	82.6	88.5	94.5	100.5	106.4
78	35.2	41.2	47.2	53.3	59.3	65.3	71.3	77.4	83.4	89.4	95.4	101.4	107.5
80	35.5	41.6	47.7	53.7	59.8	65.9	72.0	78.1	84.1	90.2	96.3	102.4	108.5
82	35.8	41.9	48.1	54.2	60.3	66.5	72.6	78.7	84.9	91.0	97.2	103.3	109.4
84	36.1	42.3	48.5	54.7	60.8	67.0	73.2	79.4	85.6	91.8	98.0	104.2	110.4
86	36.4	42.6	48.8	55.1	61.3	67.6	73.8	80.1	86.3	92.6	98.8	105.1	111.3
88	36.6	42.9	49.2	55.5	61.8	68.1	74.4	80.7	87.0	93.3	99.6	105.9	112.2
90	36.9	43.2	49.6	55.9	62.3	68.6	75.0	81.3	87.7	94.0	100.4	106.7	113.1
92	37.1	43.5	49.9	56.3	62.7	69.1	75.5	81.9	88.4	94.8	101.2	107.6	114.0
94	37.4	43.8	50.3	56.7	63.2	69.6	76.1	82.5	89.0	95.4	101.9	108.3	114.8
96	37.6	44.1	50.6	57.1	63.6	70.1	76.6	83.1	89.6	96.1	102.6	109.1	115.6
98	37.9	44.4	51.0	57.5	64.1	70.6	77.2	83.7	90.3	96.8	103.3	109.9	116.4
100	38.1	44.7	51.3	57.9	64.5	71.1	77.7	84.3	90.9	97.4	104.0	110.6	117.2

I.3.3 Tanoak

Model Name: TO_CR1_Ca
Model Form: CR1

Synopsis

The tanoak site index model TO_*CR1_Ca* is applicable to tanoak in the North Coast region of California and in the interior. The data used in fitting the site index model was primarily from the redwood zone in Humboldt and Mendocino counties. The approximate breast-high age range of the data 10 – 100 years and the site index range is 30 - 90 feet.

Figure I.31 shows site curve graphs for the MD_*SH1_Ca* model. Table I.17 provides the number of sampling locations by county for tanoak. Table I.18 provides tabular values of heights by breast-high age and site index.

Table I.17. Numbers of tanoak sampling locations by county.

County	Numbers of Stands
Butte	2
Del Norte	5
Humboldt	61
Mendocino	57
Nevada	1
Santa Cruz	3
Sonoma	7
Trinity	2
Yuba	1

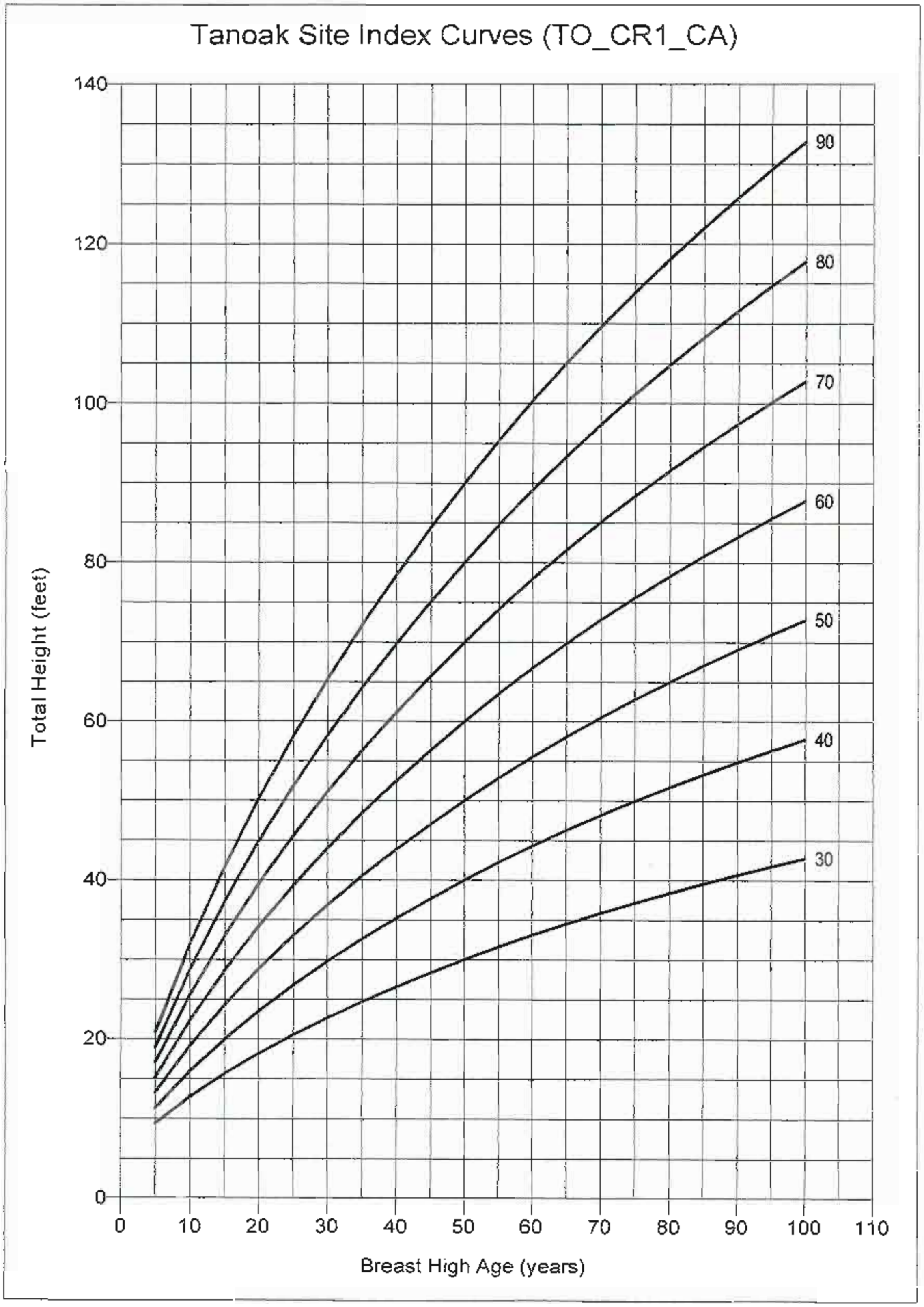

Figure I.31. *Tanoak site index curves for the TO_CR1_Ca model.*

Table I.18. Tanoak site index table for the TO_CR1_Ca model.

Tanoak Site Index Table (TO_CR1_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index														
Age	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
12	13.9	15.7	17.6	19.4	21.2	23.1	24.9	26.8	28.6	30.4	32.3	34.1	36.0	37.8	39.6
14	15.0	17.1	19.1	21.2	23.3	25.3	27.4	29.4	31.5	33.6	35.6	37.7	39.8	41.8	43.9
16	16.1	18.4	20.6	22.9	25.2	27.5	29.7	32.0	34.3	36.6	38.8	41.1	43.4	45.6	47.9
18	17.1	19.6	22.1	24.6	27.0	29.5	32.0	34.5	36.9	39.4	41.9	44.4	46.8	49.3	51.8
20	18.1	20.8	23.5	26.1	28.8	31.5	34.2	36.8	39.5	42.2	44.8	47.5	50.2	52.9	55.5
22	19.1	21.9	24.8	27.7	30.5	33.4	36.3	39.1	42.0	44.8	47.7	50.6	53.4	56.3	59.1
24	20.0	23.1	26.1	29.1	32.2	35.2	38.3	41.3	44.4	47.4	50.4	53.5	56.5	59.6	62.6
26	20.9	24.1	27.4	30.6	33.8	37.0	40.2	43.5	46.7	49.9	53.1	56.3	59.5	62.8	66.0
28	21.8	25.2	28.6	32.0	35.4	38.7	42.1	45.5	48.9	52.3	55.7	59.1	62.5	65.9	69.3
30	22.6	26.2	29.8	33.3	36.9	40.4	44.0	47.5	51.1	54.6	58.2	61.8	65.3	68.9	72.4
32	23.5	27.2	30.9	34.6	38.3	42.1	45.8	49.5	53.2	56.9	60.6	64.4	68.1	71.8	75.5
34	24.3	28.1	32.0	35.9	39.8	43.6	47.5	51.4	55.3	59.1	63.0	66.9	70.8	74.6	78.5
36	25.0	29.1	33.1	37.1	41.2	45.2	49.2	53.2	57.3	61.3	65.3	69.4	73.4	77.4	81.4
38	25.8	30.0	34.2	38.3	42.5	46.7	50.9	55.0	59.2	63.4	67.6	71.8	75.9	80.1	84.3
40	26.5	30.9	35.2	39.5	43.8	48.2	52.5	56.8	61.1	65.5	69.8	74.1	78.4	82.7	87.1
42	27.3	31.7	36.2	40.7	45.1	49.6	54.1	58.5	63.0	67.5	71.9	76.4	80.8	85.3	89.8
44	28.0	32.6	37.2	41.8	46.4	51.0	55.6	60.2	64.8	69.4	74.0	78.6	83.2	87.8	92.4
46	28.7	33.4	38.1	42.9	47.6	52.4	57.1	61.8	66.6	71.3	76.1	80.8	85.5	90.3	95.0
48	29.3	34.2	39.1	44.0	48.8	53.7	58.6	63.4	68.3	73.2	78.0	82.9	87.8	92.7	97.5
50	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0
52	30.6	35.8	40.9	46.0	51.2	56.3	61.4	66.5	71.7	76.8	81.9	87.0	92.2	97.3	102.4
54	31.3	36.5	41.8	47.0	52.3	57.5	62.8	68.0	73.3	78.5	83.8	89.0	94.3	99.5	104.8
56	31.9	37.3	42.6	48.0	53.4	58.7	64.1	69.5	74.9	80.2	85.6	91.0	96.3	101.7	107.1
58	32.5	38.0	43.5	49.0	54.5	59.9	65.4	70.9	76.4	81.9	87.4	92.9	98.4	103.9	109.3
60	33.1	38.7	44.3	49.9	55.5	61.1	66.7	72.3	77.9	83.5	89.1	94.7	100.4	106.0	111.6
62	33.7	39.4	45.1	50.8	56.5	62.3	68.0	73.7	79.4	85.1	90.9	96.6	102.3	108.0	113.7
64	34.2	40.1	45.9	51.7	57.6	63.4	69.2	75.0	80.9	86.7	92.5	98.4	104.2	110.0	115.9
66	34.8	40.7	46.7	52.6	58.5	64.5	70.4	76.4	82.3	88.2	94.2	100.1	106.1	112.0	117.9
68	35.3	41.4	47.4	53.5	59.5	65.6	71.6	77.7	83.7	89.7	95.8	101.8	107.9	113.9	120.0
70	35.9	42.0	48.2	54.3	60.5	66.6	72.8	78.9	85.1	91.2	97.4	103.5	109.7	115.8	122.0
72	36.4	42.6	48.9	55.2	61.4	67.7	73.9	80.2	86.4	92.7	98.9	105.2	111.4	117.7	123.9
74	36.9	43.3	49.6	56.0	62.3	68.7	75.0	81.4	87.7	94.1	100.4	106.8	113.1	119.5	125.9
76	37.4	43.9	50.3	56.8	63.2	69.7	76.1	82.6	89.0	95.5	101.9	108.4	114.8	121.3	127.7
78	37.9	44.5	51.0	57.5	64.1	70.6	77.2	83.7	90.3	96.8	103.4	109.9	116.5	123.0	129.6
80	38.4	45.0	51.7	58.3	65.0	71.6	78.3	84.9	91.5	98.2	104.8	111.5	118.1	124.8	131.4
82	38.9	45.6	52.3	59.1	65.8	72.5	79.3	86.0	92.8	99.5	106.2	113.0	119.7	126.4	133.2
84	39.3	46.2	53.0	59.8	66.6	73.5	80.3	87.1	94.0	100.8	107.6	114.4	121.3	128.1	134.9
86	39.8	46.7	53.6	60.5	67.5	74.4	81.3	88.2	95.1	102.1	109.0	115.9	122.8	129.7	136.6
88	40.2	47.2	54.2	61.3	68.3	75.3	82.3	89.3	96.3	103.3	110.3	117.3	124.3	131.3	138.3
90	40.7	47.8	54.9	62.0	69.0	76.1	83.2	90.3	97.4	104.5	111.6	118.7	125.8	132.9	140.0
92	41.1	48.3	55.5	62.6	69.8	77.0	84.2	91.4	98.5	105.7	112.9	120.1	127.2	134.4	141.6
94	41.5	48.8	56.1	63.3	70.6	77.8	85.1	92.4	99.6	106.9	114.1	121.4	128.7	135.9	143.2
96	41.9	49.3	56.6	64.0	71.3	78.7	86.0	93.4	100.7	108.0	115.4	122.7	130.1	137.4	144.8
98	42.4	49.8	57.2	64.6	72.1	79.5	86.9	94.3	101.7	109.2	116.6	124.0	131.4	138.9	146.3
100	42.8	50.3	57.8	65.3	72.8	80.3	87.8	95.3	102.8	110.3	117.8	125.3	132.8	140.3	147.8

I.3.4 Black Oak

Model Name: BO_LG1_Ca
Model Form: LG1

Synopsis

The black oak site index model BO_*LG1_Ca* is applicable to black oak primarily in the interior regions of California. The data used in fitting the site index model was primarily from interior low elevation mixed conifer sites surrounding the Sacramento – San Juaquin valleys. The approximate breast-high age range of the data 10 – 100 years and the site index range is 20 - 80 feet.

Figure I.32 shows site curve graphs for the *BO_LG1_Ca* model. Table I.19 provides the number of sampling locations by county for black oak. Table I.20 provides tabular values of heights by breast-high age and site index.

Table I.19. Numbers of black oak sampling locations by county.

County	Numbers of Stands
Butte	8
Calaveras	1
El Dorado	1
Humboldt	3
Kern	1
Lake	2
Lassen	1
Mendocino	7
Modoc	1
Napa	1
Nevada	1
Placer	2
Plumas	4
Shasta	13
Siskiyou	2
Sonoma	3
Tehama	1
Trinity	1
Tulare	2
Tuolumne	1
Yuba	2

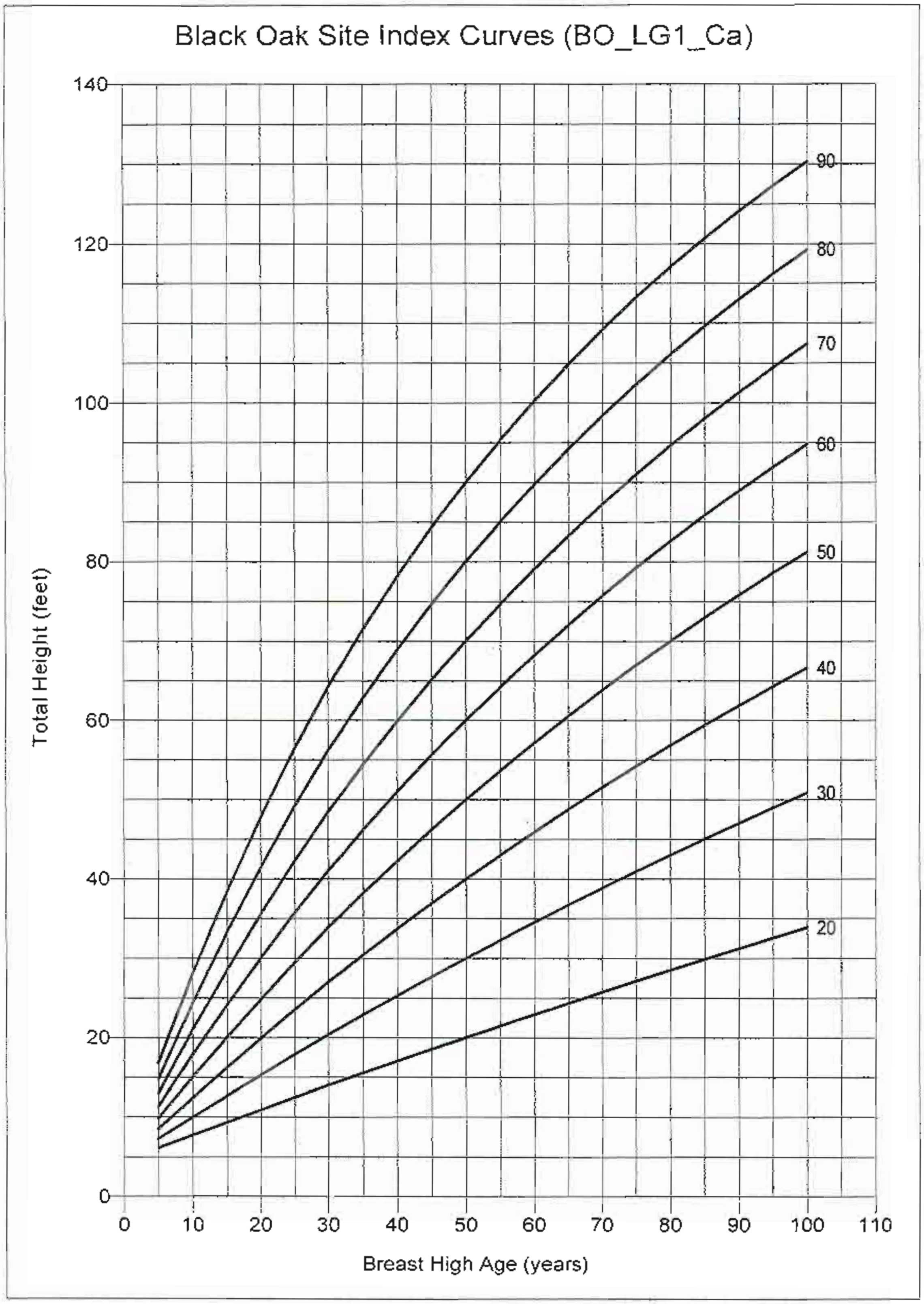

Figure I.32. *Black oak site index curves for the BO_LG1_Ca model.*

Table I.20. Black oak site index table for the BO_LG1_Ca model.

Black Oak Site Index Table (BO_LG1_Ca)
Tabled values are total height in feet

BH Age	50 Year Breast-High Base Age Site Index														
	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
12	8.3	9.7	11.0	12.5	13.9	15.5	17.0	18.7	20.4	22.2	24.1	26.0	28.0	30.2	32.4
14	9.0	10.5	12.1	13.7	15.4	17.2	19.0	20.9	22.9	24.9	27.1	29.3	31.6	34.0	36.4
16	9.6	11.4	13.2	15.0	17.0	18.9	21.0	23.1	25.3	27.6	30.0	32.4	35.0	37.6	40.4
18	10.2	12.2	14.2	16.3	18.4	20.7	22.9	25.3	27.7	30.2	32.8	35.5	38.3	41.2	44.2
20	10.9	13.0	15.3	17.6	19.9	22.3	24.8	27.4	30.1	32.8	35.6	38.5	41.5	44.6	47.8
22	11.5	13.9	16.3	18.8	21.4	24.0	26.7	29.5	32.3	35.3	38.3	41.4	44.6	47.9	51.3
24	12.1	14.7	17.3	20.0	22.8	25.6	28.5	31.5	34.6	37.7	41.0	44.3	47.6	51.1	54.7
26	12.7	15.5	18.4	21.3	24.2	27.3	30.4	33.5	36.8	40.1	43.5	47.0	50.6	54.3	58.0
28	13.4	16.3	19.4	22.5	25.6	28.8	32.1	35.5	38.9	42.4	46.0	49.7	53.4	57.3	61.2
30	14.0	17.2	20.4	23.7	27.0	30.4	33.9	37.4	41.0	44.7	48.5	52.3	56.2	60.2	64.2
32	14.6	18.0	21.4	24.9	28.4	32.0	35.6	39.3	43.1	47.0	50.9	54.8	58.9	63.0	67.2
34	15.2	18.8	22.4	26.0	29.7	33.5	37.3	41.2	45.1	49.1	53.2	57.3	61.5	65.7	70.1
36	15.8	19.6	23.3	27.2	31.1	35.0	39.0	43.0	47.1	51.3	55.5	59.7	64.0	68.4	72.8
38	16.4	20.4	24.3	28.3	32.4	36.5	40.6	44.8	49.1	53.4	57.7	62.1	66.5	71.0	75.5
40	17.0	21.1	25.3	29.5	33.7	38.0	42.3	46.6	51.0	55.4	59.9	64.4	68.9	73.5	78.1
42	17.6	21.9	26.2	30.6	35.0	39.4	43.9	48.3	52.9	57.4	62.0	66.6	71.2	75.9	80.6
44	18.2	22.7	27.2	31.7	36.3	40.8	45.4	50.0	54.7	59.4	64.1	68.8	73.5	78.3	83.1
46	18.8	23.5	28.1	32.8	37.5	42.2	47.0	51.7	56.5	61.3	66.1	70.9	75.7	80.6	85.5
48	19.4	24.2	29.1	33.9	38.8	43.6	48.5	53.4	58.3	63.2	68.1	73.0	77.9	82.8	87.8
50	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0
52	20.6	25.8	30.9	36.1	41.2	46.3	51.5	56.6	61.7	66.8	71.9	77.0	82.0	87.1	92.2
54	21.2	26.5	31.8	37.1	42.4	47.7	52.9	58.2	63.4	68.6	73.8	78.9	84.0	89.2	94.3
56	21.8	27.3	32.7	38.2	43.6	49.0	54.4	59.7	65.0	70.3	75.6	80.8	86.0	91.2	96.3
58	22.3	28.0	33.6	39.2	44.8	50.3	55.8	61.2	66.6	72.0	77.3	82.6	87.9	93.1	98.3
60	22.9	28.7	34.5	40.3	45.9	51.6	57.2	62.7	68.2	73.7	79.1	84.4	89.7	95.0	100.3
62	23.5	29.5	35.4	41.3	47.1	52.8	58.5	64.2	69.8	75.3	80.8	86.2	91.6	96.9	102.1
64	24.0	30.2	36.3	42.3	48.2	54.1	59.9	65.6	71.3	76.9	82.4	87.9	93.3	98.7	104.0
66	24.6	30.9	37.1	43.3	49.3	55.3	61.2	67.0	72.8	78.5	84.1	89.6	95.1	100.4	105.8
68	25.2	31.7	38.0	44.3	50.5	56.5	62.5	68.4	74.3	80.0	85.7	91.2	96.7	102.2	107.5
70	25.7	32.4	38.9	45.3	51.5	57.7	63.8	69.8	75.7	81.5	87.2	92.9	98.4	103.8	109.2
72	26.3	33.1	39.7	46.2	52.6	58.9	65.1	71.2	77.1	83.0	88.8	94.4	100.0	105.5	110.9
74	26.9	33.8	40.5	47.2	53.7	60.1	66.4	72.5	78.5	84.5	90.3	96.0	101.6	107.1	112.5
76	27.4	34.5	41.4	48.2	54.8	61.2	67.6	73.8	79.9	85.9	91.8	97.5	103.1	108.6	114.1
78	28.0	35.2	42.2	49.1	55.8	62.4	68.8	75.1	81.3	87.3	93.2	99.0	104.6	110.2	115.6
80	28.5	35.9	43.0	50.0	56.8	63.5	70.0	76.4	82.6	88.7	94.6	100.4	106.1	111.7	117.1
82	29.1	36.6	43.8	51.0	57.9	64.6	71.2	77.6	83.9	90.0	96.0	101.8	107.5	113.1	118.6
84	29.6	37.2	44.6	51.9	58.9	65.7	72.4	78.9	85.2	91.4	97.4	103.2	108.9	114.5	120.0
86	30.1	37.9	45.4	52.8	59.9	66.8	73.5	80.1	86.5	92.7	98.7	104.6	110.3	115.9	121.4
88	30.7	38.6	46.2	53.7	60.9	67.9	74.7	81.3	87.7	94.0	100.0	105.9	111.7	117.3	122.7
90	31.2	39.3	47.0	54.6	61.9	68.9	75.8	82.5	88.9	95.2	101.3	107.2	113.0	118.6	124.1
92	31.7	39.9	47.8	55.5	62.8	70.0	76.9	83.6	90.1	96.5	102.6	108.5	114.3	119.9	125.4
94	32.3	40.6	48.6	56.3	63.8	71.0	78.0	84.8	91.3	97.7	103.8	109.8	115.6	121.2	126.6
96	32.8	41.2	49.4	57.2	64.8	72.0	79.1	85.9	92.5	98.9	105.1	111.0	116.8	122.4	127.9
98	33.3	41.9	50.1	58.1	65.7	73.1	80.2	87.0	93.7	100.1	106.3	112.2	118.0	123.7	129.1
100	33.9	42.6	50.9	58.9	66.6	74.1	81.2	88.1	94.8	101.2	107.4	113.4	119.2	124.9	130.3

I.3.5 Other Oaks

Model Name: OO_SH1_Ca
Model Form: SH1

Synopsis

Data from five major oak species (California live oak, Oregon white oak, blue oak, interior live oak, canyon live oak) were used to make a composite site index model, OO_SH1_Ca. This model is applicable to woodland oaks wherever they are found throughout California. The approximate breast-high age range of the data 20 – 110 years and the site index range is 15 - 60 feet.

Figure I.33 shows site curve graphs for the *OO_SH1_Ca* model. Table I.21 provides the number of sampling locations by county for black oak. Table I.22 provides tabular values of heights by breast-high age and site index.

Table I.21. Numbers of woodland oak sampling locations by county.

County	Number of Stands
Alameda	4
Amador	4
Butte	14
Calaveras	5
Colusa	3
Contra Costa	2
El Dorado	9
Fresno	5
Humboldt	16
Kern	7
Lake	4
Lassen	1
Madera	3
Mariposa	9
Mendocino	18
Monterey	10
Napa	1
Nevada	3
Placer	4
Sacramento	1
San Benito	5
San Diego	1
San Joaquin	1
San Luis Obispo	5
San Mateo	1
Santa Barbara	2
Santa Clara	7
Santa Cruz	5

County	Number of Stands
Shasta	17
Siskiyou	4
Sonoma	12
Stanislaus	4
Tehama	17
Trinity	8
Tulare	8
Tuolumne	4
Ventura	1
Yolo	2
Yuba	1

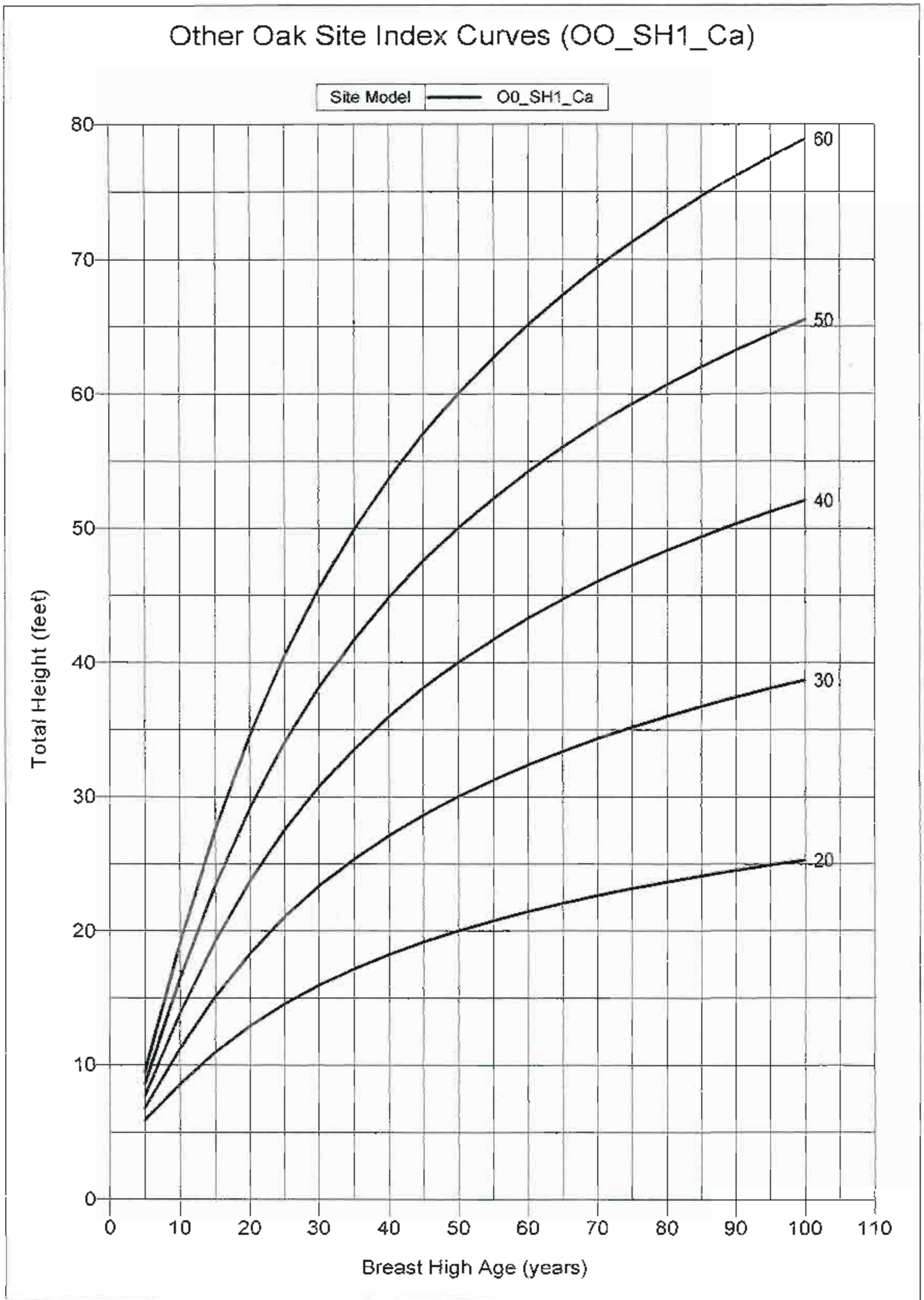

Figure I.33. *Other oak site index table for the OO_SH1_Ca model.*

Table I.22. Other oak site index table for the OO_SH1_Ca model.

Other Oak Site Index Table (OO_SH1_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index										
Age	20	25	30	35	40	45	50	55	60	65	70
12	10.1	11.9	13.7	15.4	17.2	19.0	20.8	22.6	24.4	26.2	28.0
14	10.7	12.7	14.7	16.7	18.7	20.7	22.8	24.8	26.8	28.8	30.8
16	11.3	13.6	15.8	18.0	20.2	22.4	24.6	26.8	29.0	31.2	33.4
18	12.0	14.4	16.8	19.2	21.6	24.0	26.4	28.8	31.2	33.6	36.0
20	12.5	15.1	17.7	20.3	22.9	25.5	28.1	30.7	33.3	35.9	38.5
22	13.1	15.9	18.7	21.4	24.2	27.0	29.8	32.5	35.3	38.1	40.9
24	13.7	16.6	19.6	22.5	25.5	28.4	31.4	34.4	37.3	40.3	43.2
26	14.2	17.3	20.5	23.6	26.7	29.9	33.0	36.1	39.3	42.4	45.5
28	14.7	18.0	21.3	24.6	27.9	31.2	34.5	37.8	41.1	44.5	47.8
30	15.3	18.7	22.2	25.7	29.1	32.6	36.1	39.5	43.0	46.5	49.9
32	15.8	19.4	23.0	26.7	30.3	33.9	37.6	41.2	44.8	48.5	52.1
34	16.3	20.1	23.9	27.6	31.4	35.2	39.0	42.8	46.6	50.4	54.2
36	16.8	20.7	24.7	28.6	32.6	36.5	40.5	44.4	48.4	52.3	56.3
38	17.2	21.3	25.5	29.6	33.7	37.8	41.9	46.0	50.1	54.2	58.3
40	17.7	22.0	26.2	30.5	34.8	39.0	43.3	47.6	51.8	56.1	60.3
42	18.2	22.6	27.0	31.4	35.8	40.3	44.7	49.1	53.5	57.9	62.3
44	18.6	23.2	27.8	32.3	36.9	41.5	46.0	50.6	55.2	59.7	64.3
46	19.1	23.8	28.5	33.2	37.9	42.7	47.4	52.1	56.8	61.5	66.2
48	19.6	24.4	29.3	34.1	39.0	43.8	48.7	53.5	58.4	63.3	68.1
50	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0
52	20.4	25.6	30.7	35.9	41.0	46.2	51.3	56.4	61.6	66.7	71.9
54	20.9	26.2	31.4	36.7	42.0	47.3	52.6	57.9	63.1	68.4	73.7
56	21.3	26.7	32.1	37.6	43.0	48.4	53.8	59.3	64.7	70.1	75.5
58	21.7	27.3	32.8	38.4	44.0	49.5	55.1	60.6	66.2	71.8	77.3
60	22.2	27.8	33.5	39.2	44.9	50.6	56.3	62.0	67.7	73.4	79.1
62	22.6	28.4	34.2	40.1	45.9	51.7	57.5	63.4	69.2	75.0	80.9
64	23.0	28.9	34.9	40.9	46.8	52.8	58.8	64.7	70.7	76.7	82.6
66	23.4	29.5	35.6	41.7	47.8	53.9	60.0	66.1	72.2	78.3	84.3
68	23.8	30.0	36.3	42.5	48.7	54.9	61.2	67.4	73.6	79.8	86.1
70	24.2	30.6	36.9	43.3	49.6	56.0	62.3	68.7	75.1	81.4	87.8
72	24.6	31.1	37.6	44.1	50.5	57.0	63.5	70.0	76.5	83.0	89.5
74	25.0	31.6	38.2	44.8	51.5	58.1	64.7	71.3	77.9	84.5	91.1
76	25.4	32.1	38.9	45.6	52.4	59.1	65.8	72.6	79.3	86.0	92.8
78	25.8	32.6	39.5	46.4	53.2	60.1	67.0	73.8	80.7	87.6	94.4
80	26.2	33.2	40.2	47.1	54.1	61.1	68.1	75.1	82.1	89.1	96.1
82	26.6	33.7	40.8	47.9	55.0	62.1	69.2	76.4	83.5	90.6	97.7
84	26.9	34.2	41.4	48.6	55.9	63.1	70.4	77.6	84.8	92.1	99.3
86	27.3	34.7	42.0	49.4	56.8	64.1	71.5	78.8	86.2	93.5	100.9
88	27.7	35.2	42.7	50.1	57.6	65.1	72.6	80.1	87.5	95.0	102.5
90	28.1	35.7	43.3	50.9	58.5	66.1	73.7	81.3	88.9	96.5	104.1
92	28.4	36.2	43.9	51.6	59.3	67.0	74.8	82.5	90.2	97.9	105.6
94	28.8	36.6	44.5	52.3	60.2	68.0	75.8	83.7	91.5	99.4	107.2
96	29.2	37.1	45.1	53.0	61.0	69.0	76.9	84.9	92.8	100.8	108.8
98	29.5	37.6	45.7	53.8	61.8	69.9	78.0	86.1	94.1	102.2	110.3
100	29.9	38.1	46.3	54.5	62.7	70.9	79.1	87.2	95.4	103.6	111.8

I.3.6 California Laurel

Model Name: CL_SH1_Ca
Model Form: SH1

Synopsis

California laurel (bay) is mainly concentrated in the Northern and Central California Coast ranges ecological sections. It also has a fairly scattered but widespread distribution in the interior but seldom as an associate in commercial forest timber types. The approximate breast-high age range of the data 30 – 90 years and the site index range is 30 - 70 feet.

Figure I.34 shows site curve graphs for the *CL_SH1_Ca* model. Table I.23 provides the number of sampling locations by county for black oak. Table I.24 provides tabular values of heights by breast-high age and site index.

Table I.23. Numbers of California laurel sampling locations by county.

County	Numbers of Stands
Contra Costa	1
Humboldt	5
Lake	1
Marin	1
Mendocino	4
San Mateo	1
Santa Cruz	1
Sonoma	3
Trinity	1

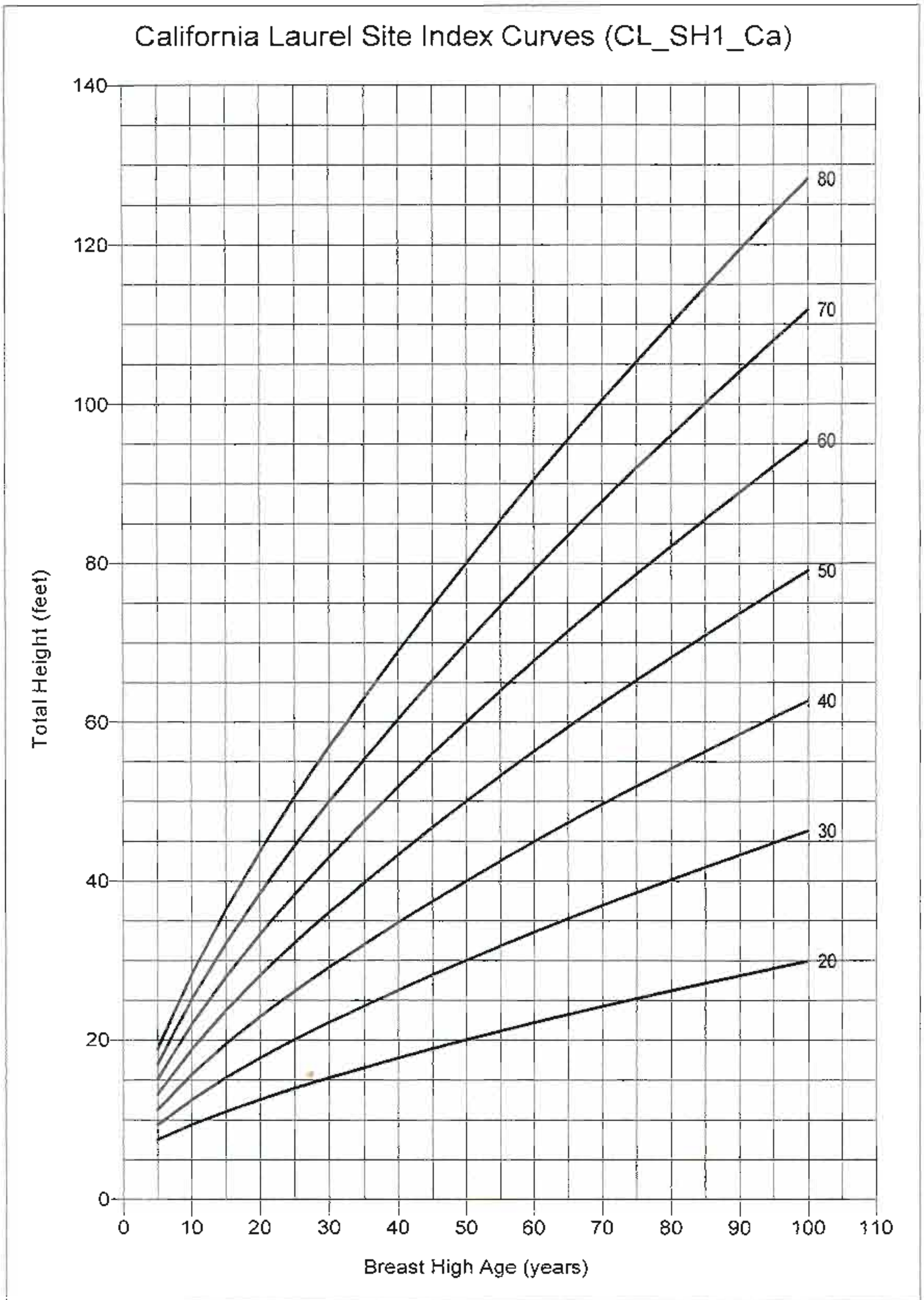

Figure I.34. *California laurel site index curves for the CL_SH1_Ca model.*

Table I.24. California laurel site index table for the CL_SH1_Ca model.

California Laurel Site Index table (CL_SH1_Ca)
Tabled values are total height in feet

BH	50 Year Breast-High Base Age Site Index												
Age	20	25	30	35	40	45	50	55	60	65	70	75	80
12	10.1	11.9	13.7	15.4	17.2	19.0	20.8	22.6	24.4	26.2	28.0	29.8	31.6
14	10.7	12.7	14.7	16.7	18.7	20.7	22.8	24.8	26.8	28.8	30.8	32.8	34.8
16	11.3	13.6	15.8	18.0	20.2	22.4	24.6	26.8	29.0	31.2	33.4	35.6	37.8
18	12.0	14.4	16.8	19.2	21.6	24.0	26.4	28.8	31.2	33.6	36.0	38.4	40.8
20	12.5	15.1	17.7	20.3	22.9	25.5	28.1	30.7	33.3	35.9	38.5	41.1	43.7
22	13.1	15.9	18.7	21.4	24.2	27.0	29.8	32.5	35.3	38.1	40.9	43.7	46.4
24	13.7	16.6	19.6	22.5	25.5	28.4	31.4	34.4	37.3	40.3	43.2	46.2	49.1
26	14.2	17.3	20.5	23.6	26.7	29.9	33.0	36.1	39.3	42.4	45.5	48.6	51.8
28	14.7	18.0	21.3	24.6	27.9	31.2	34.5	37.8	41.1	44.5	47.8	51.1	54.4
30	15.3	18.7	22.2	25.7	29.1	32.6	36.1	39.5	43.0	46.5	49.9	53.4	56.9
32	15.8	19.4	23.0	26.7	30.3	33.9	37.6	41.2	44.8	48.5	52.1	55.7	59.4
34	16.3	20.1	23.9	27.6	31.4	35.2	39.0	42.8	46.6	50.4	54.2	58.0	61.8
36	16.8	20.7	24.7	28.6	32.6	36.5	40.5	44.4	48.4	52.3	56.3	60.2	64.2
38	17.2	21.3	25.5	29.6	33.7	37.8	41.9	46.0	50.1	54.2	58.3	62.4	66.5
40	17.7	22.0	26.2	30.5	34.8	39.0	43.3	47.6	51.8	56.1	60.3	64.6	68.9
42	18.2	22.6	27.0	31.4	35.8	40.3	44.7	49.1	53.5	57.9	62.3	66.7	71.2
44	18.6	23.2	27.8	32.3	36.9	41.5	46.0	50.6	55.2	59.7	64.3	68.8	73.4
46	19.1	23.8	28.5	33.2	37.9	42.7	47.4	52.1	56.8	61.5	66.2	70.9	75.6
48	19.6	24.4	29.3	34.1	39.0	43.8	48.7	53.5	58.4	63.3	68.1	73.0	77.8
50	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0
52	20.4	25.6	30.7	35.9	41.0	46.2	51.3	56.4	61.6	66.7	71.9	77.0	82.1
54	20.9	26.2	31.4	36.7	42.0	47.3	52.6	57.9	63.1	68.4	73.7	79.0	84.3
56	21.3	26.7	32.1	37.6	43.0	48.4	53.8	59.3	64.7	70.1	75.5	80.9	86.4
58	21.7	27.3	32.8	38.4	44.0	49.5	55.1	60.6	66.2	71.8	77.3	82.9	88.4
60	22.2	27.8	33.5	39.2	44.9	50.6	56.3	62.0	67.7	73.4	79.1	84.8	90.5
62	22.6	28.4	34.2	40.1	45.9	51.7	57.5	63.4	69.2	75.0	80.9	86.7	92.5
64	23.0	28.9	34.9	40.9	46.8	52.8	58.8	64.7	70.7	76.7	82.6	88.6	94.5
66	23.4	29.5	35.6	41.7	47.8	53.9	60.0	66.1	72.2	78.3	84.3	90.4	96.5
68	23.8	30.0	36.3	42.5	48.7	54.9	61.2	67.4	73.6	79.8	86.1	92.3	98.5
70	24.2	30.6	36.9	43.3	49.6	56.0	62.3	68.7	75.1	81.4	87.8	94.1	100.5
72	24.6	31.1	37.6	44.1	50.5	57.0	63.5	70.0	76.5	83.0	89.5	95.9	102.4
74	25.0	31.6	38.2	44.8	51.5	58.1	64.7	71.3	77.9	84.5	91.1	97.7	104.4
76	25.4	32.1	38.9	45.6	52.4	59.1	65.8	72.6	79.3	86.0	92.8	99.5	106.3
78	25.8	32.6	39.5	46.4	53.2	60.1	67.0	73.8	80.7	87.6	94.4	101.3	108.2
80	26.2	33.2	40.2	47.1	54.1	61.1	68.1	75.1	82.1	89.1	96.1	103.1	110.1
82	26.6	33.7	40.8	47.9	55.0	62.1	69.2	76.4	83.5	90.6	97.7	104.8	111.9
84	26.9	34.2	41.4	48.6	55.9	63.1	70.4	77.6	84.8	92.1	99.3	106.5	113.8
86	27.3	34.7	42.0	49.4	56.8	64.1	71.5	78.8	86.2	93.5	100.9	108.3	115.6
88	27.7	35.2	42.7	50.1	57.6	65.1	72.6	80.1	87.5	95.0	102.5	110.0	117.5
90	28.1	35.7	43.3	50.9	58.5	66.1	73.7	81.3	88.9	96.5	104.1	111.7	119.3
92	28.4	36.2	43.9	51.6	59.3	67.0	74.8	82.5	90.2	97.9	105.6	113.4	121.1
94	28.8	36.6	44.5	52.3	60.2	68.0	75.8	83.7	91.5	99.4	107.2	115.0	122.9
96	29.2	37.1	45.1	53.0	61.0	69.0	76.9	84.9	92.8	100.8	108.8	116.7	124.7
98	29.5	37.6	45.7	53.8	61.8	69.9	78.0	86.1	94.1	102.2	110.3	118.4	126.4
100	29.9	38.1	46.3	54.5	62.7	70.9	79.1	87.2	95.4	103.6	111.8	120.0	128.2

Appendix II: Evaluation of Model Construction Methods

This appendix provides a general overview and a description of statistical issues and methods that have been employed to estimate global parameters of the base age invariant site index models developed in the course of this study. The main objective in constructing site index models in this study is, for a particular species or group of species in a specific location, to find the model that best describes the long term height growth development of dominant and co-dominant trees. 'Best' is meant to imply unbiased parameter estimates that are of minimum variance.

II.1 Conceptual Modeling Framework

In this study, trees are used as the primary unit of analysis as it allows the most breadth in the use of available data.

Conceptually, we can consider every 'free-to-grow' tree to have its own pre-ordained height over age curve. This is designated as the *local tree model*. This curve will never be fully observed until the tree is terminated – either naturally or culturally. At any age, the *actual height* of the tree will be its 'prediction' from the local model plus the sum of all previous annual deviations from the curve. What the *observed height* will be at any age is the actual height of the tree plus measurement error.

If local tree models are assumed to be of the same form as a global population model, then local tree model parameters can be considered random variables with expected values equal to global model parameters and concomitant distributional properties of multivariate normality.

II.2 Statistical Estimation Issues

In estimating parameters of base age invariant site index models there are two main but interrelated issues: a) how to order the data into dependent and independent variables (X's and Y's) and b) the estimation procedures to employ.

With traditional base age specific models ($H=f(H_s, A)$ or $H_s = f(H,A)$), how observations are ordered is not an issue. If a height prediction model is being fitted, all of the heights with the exception of height at the base age (site index) are dependent variables. The converse is true with base age specific site prediction models.

With base age invariant models or traditional height prediction models framed as difference equations, choice of independent variables (initial conditions) and dependent variables (heights to be predicted) can be seemingly arbitrary as the X's and Y's are the same.

Cao (1993) for example, evaluated several forms of base age invariant site index models using non-overlapping forward differences (initial age is less than prediction age) and ordinary least squares (OLS) estimation techniques. Borders et al. (1988) suggested an ad hoc method consisting of using all possible combinations of height/age pairs for a specific tree as observations. Bailey and Clutter (1974) did not use any heights (site index) as dependent variables, proposing a method that estimates each site-specific parameter along with all of the global model parameters through covariance analysis. Furnival et al. (1990) compared several techniques and noted that under certain conditions for site index models that can be linearized, several solution procedures produced the same result.

Goelz and Burk (1996) have noted that tree heights are seldom measured exactly and are subject to 'measurement' error. Interpolated site index values are a good example. Whether the error is due to pure measurement or some combination involving cumulative seasonal fluctuations about a local tree model does not make any difference. When heights appear as dependent variables, they are specified to have an associated regression error. However, when they appear as independent variables, they are assumed to be error free. These are conflicting assumptions. Regardless, a primary tenet of regression analysis, namely that the X's are measured without error, is violated. Statistical theory suggests that conventional estimation techniques applied to linear regression models when the X's are not error free lead to biased parameter estimates. By extension, the problem will also persist in non-linear models.

Ages are also prone to measurement error and can further exacerbate the problem. One other primary tenet of regression analysis is that the stochastic regression errors are uncorrelated with the systematic parts (the X's). If this assumption does not hold, then conventional estimation techniques will result in biased parameter estimates. It is well known that the dependent variables in regression models are correlated with the stochastic error terms. And, as in base age invariant site index models, if the X's and Y's are essentially synonymous, then this latter assumption is also violated.

Strub and Cieszewski (2001), Cieszewski (2002) and several others have expounded on the 'measurement error' problem or in general, the fact that any 'height' that appears on the right hand side of a regression model is essentially an unobservable variable. To summarize:

a) Site index models are by nature 'self-referencing' (Northway, 1985). Heights and ages that appear on the right hand side of models should represent points on the global site index model (estimates) that cannot be evaluated until the global parameters are estimated. However, the estimated heights must be known in order to obtain unbiased estimates of the global model parameters. Using measured rather than estimated heights results in biased global model parameters.

b) Traditional height prediction models are normally conditioned to predict site index when the prediction age is equal to the base age. Failure to do so produces a site index system that is inconsistent. Forcing site curves through a fixed point that is usually specified as an observed value exacerbates bias induced by measurement and other forms of secular 'error' and results in inconsistent curve shapes when base ages are changed (Heger, 1973).

c) Base age invariant site index models framed as difference equations as in this study, force site curves through initial conditions which, if specified as 'observed' values, is analogous to what is done in traditional height prediction models.

II.2.1 Unbiased Estimation

Numerous methods have been suggested to overcome the above problems. With the exception of Goelz and Burk's proposal (1996), they all involve estimating the global site index model parameters and all of the tree heights (site indices) that appear as independent variables simultaneously. Methods that may possibly be adaptable to this study are (solution abbreviation methods appear in parentheses):

1. **Borders all combination method** (BAC). Goelz and Burk (1996) proposed an ad hoc method to deal with 'measurement' error that, among other things, prescribed the use of Borders et al. (1988) all combination method. Based on an analogy with linear principal axis regression, their rationale for using this approach when measurement error exists can loosely be paraphrased as: 'If the regression of Y on X results in parameter estimates that are biased in one direction, and the regression of X on Y results in parameter estimates biased in the opposite direction, then regressing everything on everything should balance everything out'.

2. **Forward Differences** (FD) or **Backward Differences** (BD). Bias is a matter of degree. If it is negligible, then estimating global model parameters with data ordered as forward differences or backward differences is simple and can be efficiently implemented with conventional OLS non-linear algorithms.

3. **Dummy Variable Approach** (DV). Cieszewski et al. (2000) describe a procedure employing dummy (0,1) variables that can be summarized as follows: For each tree, the initial conditions (independent variables) are specified to be the same for all tree measurements. The age can be arbitrary within limits (for example, age zero is not permissible). The initial height (H_0) is then estimated for each tree along with all of the global site index model parameters. A minimum of two measurements per tree is required. This procedure has proven to work well with small data sets (100-200 trees), particularly with models that are anamorphic in form. On large data sets (more than 800 trees), this approach can sometimes take hours to converge and often fails to converge reasonably at all.

4. **Nested Regression** (NR). This method (Cieszewski and White,1993), Strub and Cieszewski, 2002) involves the same conceptual framework as the DV method but in practice, it is much more computationally efficient and stable. The method uses a nested regression procedure. The first step is to arbitrarily assign an initial age (A_0) to each tree. This is taken to be the average of all ages in a tree's measurement sequence. An estimate of the corresponding initial height is taken to be the average of all total heights in a tree's measurement sequence. The solution procedure is iterative involving two steps at each iteration:

   a. Perform one regression iteration to estimate the global model parameters using the estimated initial heights as constants.

   b. Given updated global parameter estimates, treat them as constants and, for each tree, optimize the estimate of the initial height (find the estimated height that will minimize the residual sum of squared residuals for each tree).

Steps a) and b) are repeated until the residual sum of squares stabilizes.

5. **Iterative Evaluation Approach** (IE). The basis for this solution approach is due to Tait et. al. (1988). It was further developed as an alternative to the nested regression approach described above. The nested regression approach normally works well but sometimes 'thrashing' occurs where the global parameter and local site variable solutions oscillate back and forth without stabilizing. Also noted are the following:

    a. Performing a nonlinear regression on a small number of measurements (the height/age sequence for a single tree) where there is only one parameter to estimate is somewhat computationally excessive. This can be reduced to a simple optimization problem utilizing a univariate search algorithm that can exploit the fact that the optimization is for one variable only. The IMSL routine DUVMIF has been found to be satisfactory for this purpose (see section II.6 below).

    b. Given good starting guesses for both global model parameters and the local tree heights, the IE approach proceeds as follows: i) allow the regression to estimate the global parameters to go to completion holding the estimated local tree heights constant. ii) update the local tree height parameters after a global solution is obtained. This is done by holding the global parameters constant and optimizing the estimates of the local heights on a tree by tree basis using the DUVMIF routine; and iii) repeat the process until the change in sums of squares is negligible (10^{-5} was used here). Normally, this modification produces the same results as the nested regression procedure (site index curves appear visually as virtual overlays). Solution time however, can sometimes be reduced by over 500 percent.

Thus, the IE method was used as a general solution basis. Final solution values were than used as starting values with the nested regression procedure as a final check.

II.2.2 Compatibility

The DV, NR, and IE approaches all conceptually accomplish the same objective and, when things work right in applications, produce solutions that are practically the same. The DV approach however sometimes fails, particularly with large numbers of trees and polymorphic model forms. This solution approach was not routinely used. The preferred method was the IE approach with the NR approach used as a check.

II.2.3 Age Errors

The DV, NR, and IE approaches concentrate on estimating local unobserved site variables (heights or site indices) to produce unbiased estimates. Age errors are ignored because the site index base age or initial condition age is arbitrary. The prediction age is the problem. However, one can take the view that whatever age the prediction age was recorded as, it is the 'real' age and the one at which heights should have been measured. Age errors can then be viewed as another measurement error factor in tree heights.

II.2.4 Calendar Periods

It was decided that site index curves should nominally incorporate the average periodic influence on height growth patterns as evidenced in the 20th century (1900 – 2000). A problem exists in that observation ages in the site tree database are correlated with calendar years and it was suspected that weighting observation sets too heavily in certain calendar ranges would unduly influence the shape of resulting site curves. Preliminary analysis also indicated that, depending on the calendar periods from which observations were taken, differences in resulting site index models could sometimes be in the marginal range. This may be one source of disparity in existing site index models applicable to mixed conifer forest types. This problem could be remedied by balancing observation site index and age with calendar period. However, initial attempts indicated that over 60 percent of the data would have to be discarded if this solution procedure were to be adopted. An alternative approach was developed that allowed the retention of all data and also stabilized the influence of calendar periods. This procedure can be summarized as follows:

a) Only tree height/age data that were observed between 1898 and 2002 were used in all analyses.

b) Twenty 5-year calendar period classes (lustrums) were created and denoted as 1900, 1905...1995. The 1900 class spans the periods 1898 – 1902; the 1905 class spans the periods 1903-1907 and so on.

c) Each tree observation spans an age interval (A_0 to A) that corresponds to a calendar interval. The number of years each tree observation contributed to each of the 21 lustrums was subsequently computed and then divided by 5. These variables are denoted as z_i. For backward differences, the z_i were negated.

d) Twenty-one 'nuisance' parameters were defined that correspond to proportional growth deviations for each 5-year calendar period. These are denoted as g_1 for the 1900 calendar class, g_2 for the 1905 calendar class, etc.

e) A multiplicative term ***Z*** was subsequently defined for each observation as:

$$\boldsymbol{Z} = (1 + z_1 g_1 + z_2 g_2 + \ldots z_{21} g_{21})$$

f) Z is subsequently appended to all models in the regression analysis as a proportionate correction:

$$H = 4.5 + f(H_0, A_0, A, b_1, b_2, .. b_n)Z$$

The parameters g_1 – g_{21} are estimated simultaneously along with the global model parameters and whatever tree specific variables are necessary. To ensure that $\Sigma g_i = 0$, only 20 parameters were actually estimated and g_{21} was set to be $-\Sigma g_i$, i=1,20.

The estimated g_i represent proportional deviations from long-term growth for each five-year calendar period. While they are employed in post analysis of residuals, the g_i are eventually discarded. In several instances, the g_i sequence had to be condensed, as specific analyses did not have trees from all calendar periods available.

II.3 Mixed Conifer Empirical Comparison

In the course of this study, several existing traditional base age specific models were evaluated along with base age invariant models developed here. With numerous solution techniques implemented in the past and several available here, some empirical comparison was felt to be appropriate at an early stage to gain an idea of the magnitude of differences resulting from different solution procedures and to provide information to aid in selecting best solution procedures.

II.3.1 Data

Data to test models and solution procedures came from five stem analysis data sets: NCStem, GspPP, POPP, LDMC, and LDRF. The MC3 species group (ponderosa pine, sugar pine and interior Douglas-fir) was used as a test case. One observation set was extracted in which all stem analysis tree data series had 'measured' tree site indices (linearly interpolated from adjacent heights and ages if necessary) at ages 30 and 70. This data set consisted of 384 trees and 2486 measurements. The age span was from five to 107 years.

II.3.2 Model Forms

Base Age Invariant Model Form. The CR2 model form derived from the GADA formulated model (see chapter 3.):

$$H = 4.5 + \exp(X)[1-\exp(b_1 A)]^{(b_2 + b_3/X)}$$

has been found in general to be a versatile model for mixed conifers and is retained here as the comparative BAI model.

Base Age Specific Model Forms. Plotting empirical exponents from the fitted CR2 model against corresponding measured heights at arbitrary base ages of 30 and 70 years indicated that the following functional form for an unconstrained height prediction model would be appropriate:

Model CRa: $$H = 4.5 + c_4 S^{c_5}[1-\exp(c_1 A)]^{(c_2 S^{c_3})}$$

Where S is site index (H_s at a base age of A_s). A difference form constrained to ensure that $H = S$ when $A = A_s$ was formulated as

Model CRb. $$H = 4.5 + (S-4.5)\left[\frac{[1-\exp(c_1 A)]}{[1-\exp(c_1 A_s)]}\right]^{(c_2 S^{c_3})}$$

The CRa/CRb model forms or suitable variants have been used by several authors (Ek, 1971; Payandeh, 1974; Wensel and Krumland, 1986; Carmean and Lenthall, 1989).

II.3.3. Methods

Where appropriate, site index base ages of 30 and 70 years were arbitrarily assigned for comparative purposes. Several explicit model forms and solution procedures were specified as shown in table II.1 and subsequently tested. Starting guesses for all parameters were set to values obtained for comparable 50 year age base solutions. Trees were weighted so the sum of weights for each tree totaled one.

Table II.1. Models tested for comparative purposes.

Model Type	Model - Designator	Solution Method	Description
Base Age Invariant	CR2_Ave	IE	Height as an independent variable is estimated at the mean age of each tree's growth sequence. Starting height values for each tree are specified as the average height of all tree measurements.
	CR2_30	IE	Height was estimated at age 30 years for all trees. Starting height values were 'measured' site indices at age 30 years.
	CR2_70	IE	Height was estimated at age 70 years for all trees. Starting height values were 'measured' site indices at age 70 years.
	CR2_F	OLS[1]	Forward non-overlapping differences were used as the observation set.
	CR2_B	OLS	Backward non-overlapping differences were used as the observation set.
	CR2_AC	OLS	All combinations of measurements were used as the observation set.
Base Age Specific	CRa_30_m	OLS	30-years base age with measured site indices used as observations.
	CRa_30_e	IE	30-years base age with site indices estimated. Starting values were measured site indices.
	CRb_30_m	OLS	30-years base age with measured site indices used as observations.
	CRb_30_e	IE	30-years base age with site indices estimated. Starting values were measured site indices.
	CRa_70_m	OLS	70-years base age with measured site indices used as observations.
	CRa_70_e	IE	70-years base age with site indices estimated. Starting values were measured site indices.
	CRb_70_m	OLS	70-years base age with measured site indices used as observations.
	CRb_70_e	IE	70-years base age with site indices estimated. Starting values were measured site indices.

[1]OLS denotes ordinary non-linear least squares solution methods.

(Note: Several reviewers have taken the view that base age invariant site index models not only have the have the desired base age invariant structural properties but are also ones that have their parameters estimated by unbiased techniques. With this view, the only 'true' base age invariant models are CR2_Ave, CR2_30 and CR2_70)

II.3.4 Post Evaluation

Comparing models directly by evaluating mean square residual errors (MSE) or equivalent functions of the data as a means to determine which solution procedure is best is not totally appropriate as different sums of squares were minimized in several of the cases. Given the objective that the best site curves are the ones that best describe the long-term height growth development of site trees, a standard residual variance for each model was computed as follows:

1) Estimated global model parameters for each model were assumed to be constants.

2) For initial conditions (A_0), base ages for base age specific models were either 30 or 70 years depending on the specification. 50 years was arbitrarily assigned to base age invariant models.

3) The IMSL routine DUVMIF was used on a tree-by-tree basis to estimate the initial height (or site index) to minimize the sums of squared residuals. Denoting this value as SSR_i for tree i, a mean square error was computed as

$$MSE_i = SSR_i/(n_i-1)$$

where n_i is the number of measurements available for tree i. Note that this is exactly what happens in the final iteration of the IE/NR solution methods.

4) A pooled variance (V_k) was subsequently computed as

$$V_k = \Sigma\, MSE_i/N_k\,,\quad i = 1\ldots\ldots N_k$$

Where k denotes model k, and N_k denotes the number of trees used with model k. Ordinarily, N_k is the same for all models but in empirical evaluations some existing site index models 'fail' to be able to predict heights at some site index and age levels (see chapter 6).

5) For model k, a variance ratio (VR_k) was computed as

$$VR_k = V_k/V_{bbai}$$

where V_{bbai} denotes the comparable variance from the best base age invariant model.

The variance ratio is used as a diagnostic rather than a formal test statistic. The closer it is to 1.0, the more similar models are. With suitable refinements, the variance ratio can be used as an F-statistic. With large numbers of trees (300-400+), values less than about 1.2 would indicate models are not significantly different at conventional test levels ($\boldsymbol{p} \le .05$).

II.3.5 Results

The fitted *CR2_Ave* model and the data used in this analysis are shown in figure II.1. Visually, the model appears to describe the data quite well. Note that all of the models where height (or site index) as a parameter to be estimated appears on the right hand side of the model produce virtually coincident site index curves. These are all of the models that use the IE solution. The same results were found with the NR solution

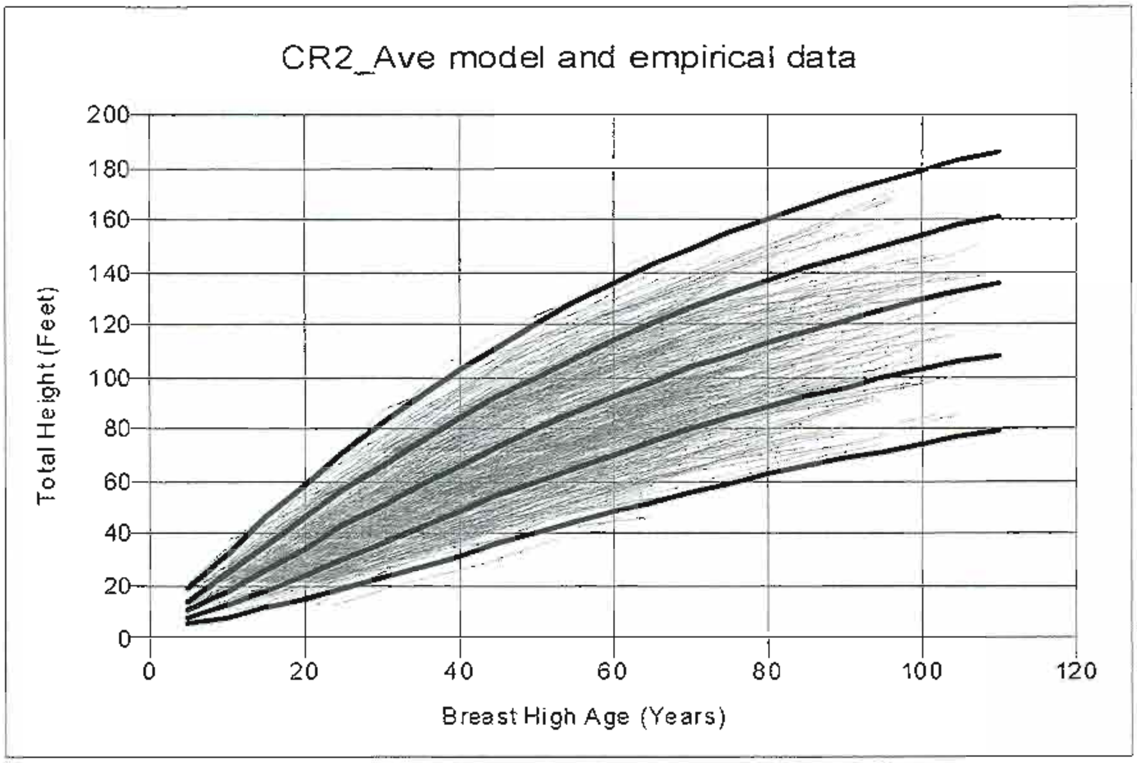

Figure II.1. *Fitted CR2_Ave model and data used in analysis.*

method. Estimating the site-specific heights is shown to provide consistent estimates across a wide range of model formulations. The *CR2_Ave* model was subsequently chosen to be representative of all models using the IE solution method.

Departures relative to the *CR2_Ave* model come in the form of all models that use some form of measured heights as variables (OLS methods). Variance ratios for these models are shown in table II.2 using the results of the *CR2_Ave* model as the basis for V_{bbai}.

Table II.2. *Variance ratios for different estimation techniques and model formulations relative to the CR2_Ave model.*

Model	VR
CR2_F	1.25
CR2_B	1.06
CR2_AC	1.08
CRa_30_m	1.07
CRb_30_m	1.09
CRa_70_m	1.03
CRb_70_m	1.05

Base Age Invariant Models

Site curves for the *CR2_Ave*, *CR2_F*, *CR2_B*, and *CR2_AC* models are shown in figure II.2 for site index levels approximately equal to the mean and the upper and lower bounds of the data. The forward difference model, both visually and in terms of variance ratios, performs the worst. In other empirical trials and sampling simulations discussed below, this has proven to be a consistent observation. The BAC method applied to the *CR2_AC* model, in spite of its intuitive appeal and recommendations by Goelz and Burk as a method that may reduce bias, appears to be the next worst method. Also note that the residual sums of squares from this method tends to be quite flat over a large solution space probably due to the somewhat redundant nature of the data (2486 tree measurements produced 15,000+ combinations). Solutions are thus sensitive to starting guesses and convergence criteria. The *CR2_B* model was closest to the *CR2_Ave* model. This was coincidental to this case. Repeating this exercise with a true fir data set showed backward differences performed quite poorly.

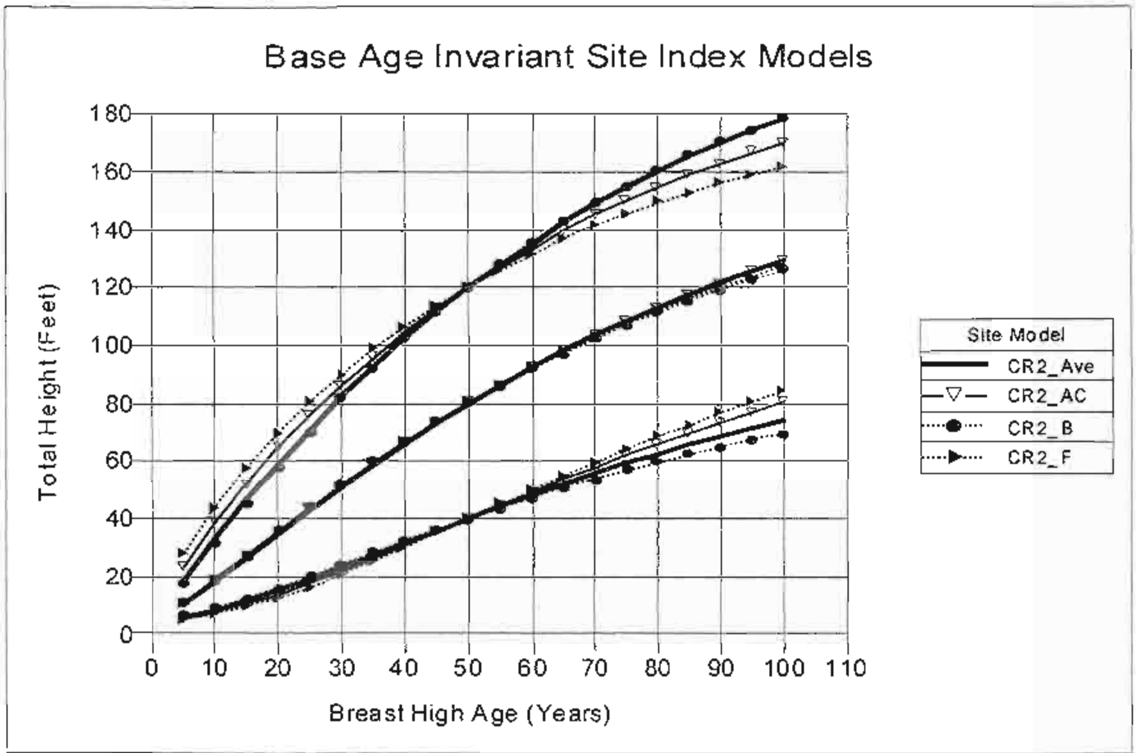

Figure II.2. *Base age invariant site index models resulting from different estimation methods.*

Base Age Specific Models

Site curves for the base age specific models estimated with OLS techniques are shown in figure II.3 along with the CR2_Ave results. All base age specific models where site index was estimated along with the global model parameters were essentially the same as the CR2_Ave model. Visually and from Table II.2, it is apparent that constraining models to pass through site index when forecast ages are equal to the base age to provide consistency results in a loss of precision. Choice of base ages however appear to result in much greater differences with the seventy year base age models being more precise than the thirty year base age results. Cieszewski (2002) offers a geometrical argument about why this should occur and it seems to hold true in the case examined here.

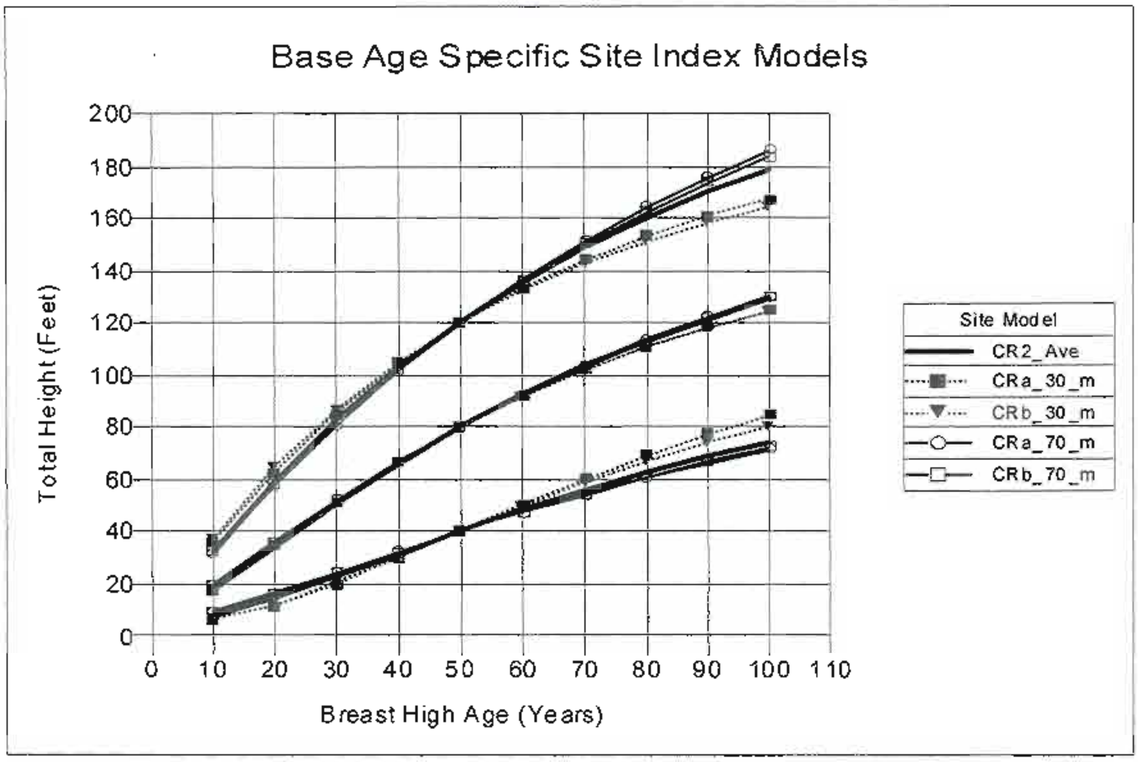

Figure II.3. *Base age specific site index models resulting from different model formulations.*

II.4 Sampling Simulations

While the previous empirical results tend to support the idea that consistent site index model parameter estimates result from methods that also estimate all heights that appear as independent model variables along with global model parameters, they are however, case specific and do not directly address the possibility of bias. Sampling simulations provide a means to examine estimation techniques from a more controlled basis. The essentials of using simulated data are:

1) Select a generating model with arbitrary parameters as the basis for true means (heights and ages).
2) Postulate various schema to account for measurement error, secular growth variation, possible bias, etc. and infuse them with the generating model to produce pseudo-growth observations series for trees.
3) Compare estimation techniques. Those that reasonably recover the shape of the generating model can be considered useful estimation techniques.

II.4.1 Stem Analysis Simulations

Estimation technique comparisons applicable to simulated stem analysis data generated with reasonable measurement error and secular variation have essentially confirmed results found in the previous empirical evaluation. Cases examined here used the CR2_Ave model and estimated parameters as a generating function. The DV, NR, and IE estimation techniques all produced site curves that were very close to the generating model. Maximum differences were seldom more than one foot and occurred in the tails of the simulated site index distribution. The OLS methods applied to both base age invariant and base age specific models all performed less precisely. The BAC method produced erratic results, particularly when simulated age/site index distributions were unbalanced. In spite of the suggestions of Goelz and Burk (1996), the BAC method cannot be considered a routine technique for consistent and unbiased site index model parameter estimation.

II.4.2 Repeated Growth Plot Measurements

Chapter four included a discussion of the possibility that breast-high ages determined by increment borings may be systematically biased, at least in comparison to comparable ages from stem analysis ring counts. For interior conifers, sufficient stem analysis data is available so growth plot measurements do not necessarily need to be used. In several situations however, they are useful in filling in gaps in regional site index/age distributions. For the Northern California Coast, virtually all redwood/Douglas-fir data are based on repeated growth plot measurements. To gain some idea of what possible effects systematic age measurement bias has on site curve parameter estimation, the following simulation was performed.

Experience has shown that growth forms of north coastal species tend to be anamorphic. The CR1 model form, suitably altered so the initial conditions are site index at a breast-high age of 50 years, was used as a generating model (CR1_Gen):

$$H = 4.5 + (S - 4.5)\left\{\frac{[1-\exp(b_1 A)]}{[1-\exp(b_1 50)]}\right\}^{b_2}$$

Generating parameters were set to be -.015 and 1, which is reasonably close to what has been found empirically. Base simulation parameters included:

1) Height measurement error is assumed to be represented by a coefficient of variation equal to five percent of true heights.

2) Observed ages were assumed to have a mean of 95 percent of the true age. The standard deviation of age measurement error was assumed to be 4 (Age/30) for ages less than 30 years and four years for ages greater than 30 years.

3) Seasonal variation was assumed to have a mean of zero and a coefficient of variation equal to six percent of growth for periods of approximately 10 years.

4) Mean 50-year breast-high age site index was assumed to be 100 feet with a standard deviation of 20 feet.

5) Measurements were assumed to be taken nominally every 10 years with a standard deviation of two years.

6) Measurement sequences were nominally generated from breast-high age of about five to 110 years.

7) One age in a measurement sequence was randomly generated with the above parameters. All other ages were taken to be the difference in calendar years from this age.

8) All ages were rounded to the nearest whole year.

Three cases were specifically examined with the IE estimation technique applied to all. An initial condition age of 50 years was arbitrarily used for all trees.

CR1_A. Pseudo growth sequences generated as described above were used as the observation set.

CR1_B. As with CR1_A, but data were trimmed on a height/age cell wise basis to remove negative height growth measurements and an equal number of measurements on faster growing trees. This resulted in roughly a 15 percent reduction in the number of pseudo observations. This procedure is described in more detail in chapter four, and was a standard basis adopted for all data used in this study.

CR1_C. As with CR1_A , but an additional 750 tree measurements were generated without an age bias. This combined data was considered to be a reasonable representation of mixed stem analysis and growth plot measurements. In fitting models, forecast ages were multiplied by an 'age difference' correction in the form of

$$(1 + d{*}c)$$

Where d is a dummy variable with a value of zero for stem analysis based measurements and one for repeated growth measurements, and c is an additional global model parameter. Parameter estimates for c are expected to be about .05 given the specified age bias used in generating the data.

II.4.3 Growth Measurement Simulation Results

Approximate 50-year breast-high age site index bounds were 60 and 140 feet. Site index levels for these values and the data mean of 100 feet are shown in figure II.4 for the generating model (CR1_Gen) and the three test cases. Visually, there is not much difference in any of the cases examined. Maximum differences from the generating model occurred at the highest site index values. Differences of each of the three cases from the generating model for a site index of 140 feet are shown in figure II.5. The unadulterated CR1_A case, while being the most different, is still within what is considered to negligible bounds in this study. The CR1_B model where data was subjected to trimming, appears to reduce biases induced by age bias and other sources of error. The CR1_C mixed data model almost recovers the underlying shape of the generating function. The estimated value of 'c' was 0.031, which was not quite the expected value of 0.05, but it was reasonably close and in the right direction.

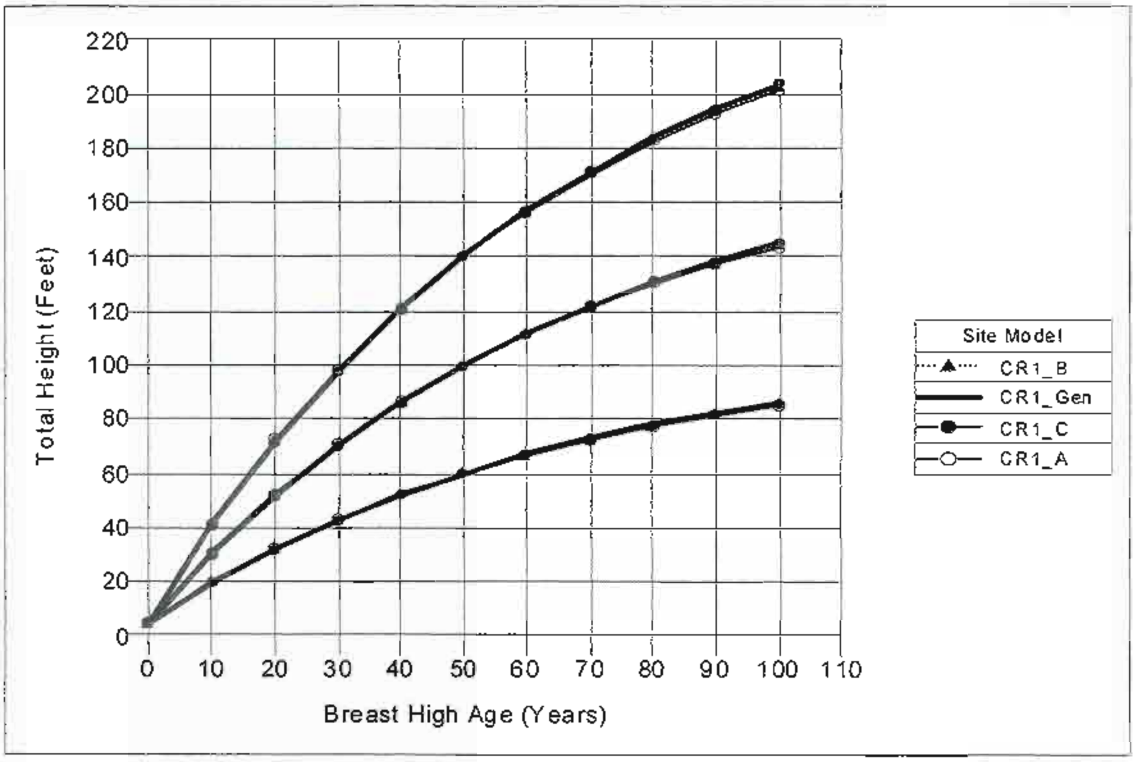

Figure II.4. *Site curves resulting from growth measurement pseudo-data.*

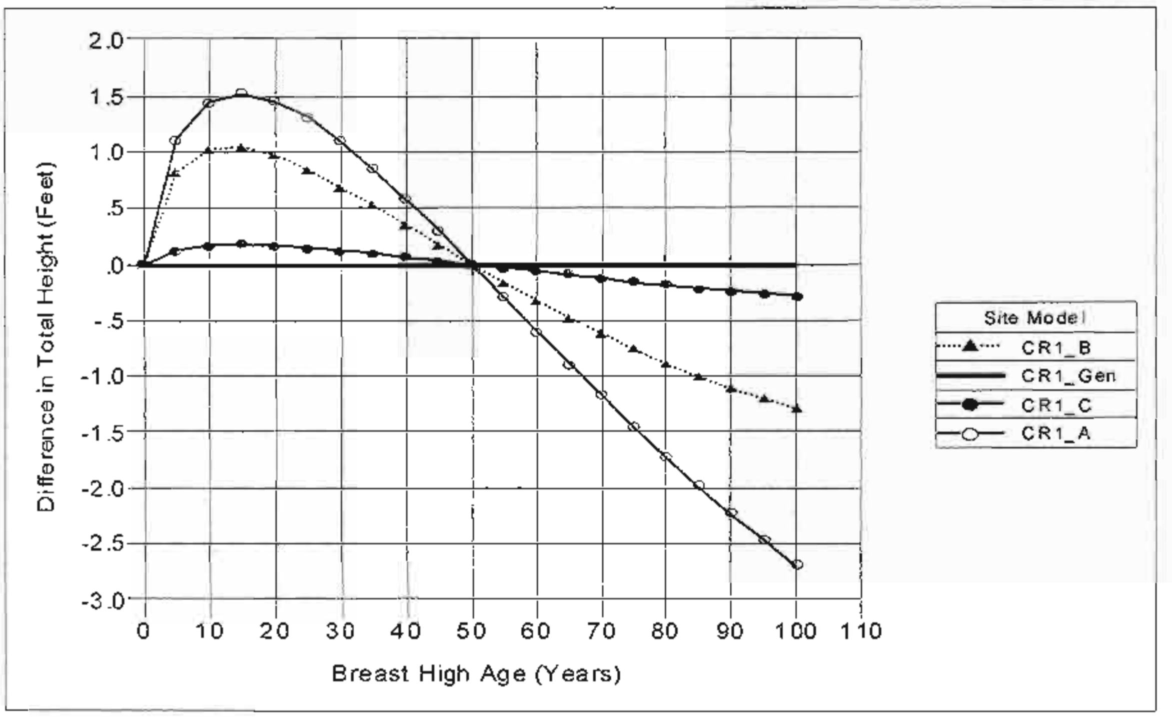

Figure II.5. *Site curve differences for a site index of 140 feet.*

II.5 Summary and Conclusions

The simulations indicate that systematic age biases resulting from increment borings of a magnitude thought to possibly exist in the data do not cause excessive site curve distortions when estimation techniques such as the NR or IE methods are employed. Age difference corrections, only possible when both stem analysis and growth plot measurements are available, appear to alleviate most of the possible problems.

Theoretically and empirically, site index model parameter estimation techniques that involve estimating all heights that appear as independent variables have shown to be both unbiased and the most precise. Consistent results are obtained with both base age invariant and base age specific model formulations. The iterative estimation method was subsequently used as the primary parameter estimation technique in all site index model development in this study.

II.6 Post Script: The Analytical Workbench

The estimation procedures used in this study are not traditional estimation processes that can be directly implemented by standard procedures available in most statistical packages. They either require extensive data table preparation, the use of software specific scripting languages (Strub and Cieszewski, 2002), or linking estimation procedures in statistical software exposed as ActiveX^{tm} software components with modern Windows^{tm} programming languages such as Visual Basic.

None of the above procedures were used here as the overall process involved fitting literally hundreds of models composed of various combinations of data sets, model forms, and estimation procedures. To automate the process as much as possible, a software program was written in Visual Basic that could integrate the various aspects of model development. Central features of the software are:

a) **Microsoft Access 2000**. Queries to extract data sets from the overall database were developed and tested with Microsoft Access and subsequently stored for later use. Microsoft Data Access Objects[tm] (DAO) software components provide the programmatic means to access and manipulate the database from within Visual Basic.

b) **International Math and Statistical Library** (IMSL). This library is a set of peer reviewed and tested mathematical and statistical procedures. Translated into various programming languages, the version used in this study was distributed with the 32-bit Windows compatible Microsoft Fortran Power Station[tm] compiler. Fortran routines can be called directly from Visual Basic. The main routines used were:

    1) DRNLIN nonlinear regression routine, which estimates parameters in nonlinear models and has a wide selection of convergence criteria that can be fine tuned for cases at hand.

    2) DRCOVB, which produces parameter variance/covariance matrices from the DRNLIN solution.

    3) DUVMIF, which finds the minimum of a univariate function. This was used in place of non-linear regression in the IE solution method for iterations involving estimating local site variables (tree heights) for each tree. Several other similar routines performed comparably. Equally effective was a 'brute force' procedure: systematically search in the neighborhood of the last estimated tree height at a desired tolerance increment (.1 feet was used in this study) until a definite minimum was found.

    4) Numerous other routines to calculate p values of parameter estimates, parameter correlation matrices, grid searches to find starting non-linear parameter estimates, etc.

c) **ActiveX components**. All GADA-based models were framed as class modules with common interfaces so they could be used in nonlinear function evaluations, graphical generation of site curves, and computations of supplementary statistics.

d) Proprietary graphics routines were also used to create function plots, scatter plots, histograms, etc.

Thus, fitting of models was reduced to:

a) Select the query that describes the data set.
b) Select the model to fit.
c) Select starting guesses.
d) Select the solution process.
e) Fit the model.
f) Process and store the results for post analysis.

Specific models that were selected for further evaluation had names assigned to them and parameter estimates and all forms of residuals were stored in database tables. The Statistica software package (StatSoft, 2003) was used to do all of the major post analysis as it is OLEDB compliant and can import database tables and queries directly from Access databases.

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