Research Note No. 13 June 30, 1985

Forest Growth and Yield Research by the Northern California Forest Yield Cooperative 1978 - 1985

by

Lee C. Wensel and Greg S. Biging

Abstract

The Northern California Forest Yield Cooperative is a joint University - forest industry organization whose overall objective is to improve the quality of growth estimates in California's conifer stands. The cooperative consists of a research team at the University, the representatives of 12 forestry companies, and other groups who have made various contributions to the work of the project. Funded by both the University (federal and state sources) and the forest industry, the University research team has worked with the industry cooperators to develop uniform definitions and field procedures to maximize the utility of the data and quality of the research results.

The industry cooperators have provided the University research team with technical assistance in planning, collected field data, and raised funds from their employers to be donated to the University in support of this work.

Now in the seventh year of the project, the major accomplishments include the development of new conifer volume and tree taper relationships, site index, tree diameter and height growth models, a computer program (**CACTOS**) to simulate growth and harvest operations and to produce yield summaries and other reports of the simulation results, and a computer program (**STAG**) that supplies estimates of missing data to enable the user to develop growth projections from stand descriptions at hand.

Future work includes the refitting and testing of the growth models using permanent plot data, the development of ingrowth and mortality models, and the development of alternative measures of productivity using soils and foliage analysis data that were collected as part of the stem analysis study. Additional validation tests are also necessary to estimate response to thinning and calibration factors for stand variables not currently considered.

The authors are Associate Professors, Department of Forestry and Resource Management, University of California, Berkeley, CA 94720.

Foreword

By the early 1970's most of the Forest Products Industry had become involved in intensive management of their forest lands. Land withdrawals and productivity restraints on public forest lands were accelerating and large acreages of non-industrial private lands were being converted to other uses. This resulted in rapidly rising stumpage prices and put pressure on the managers of the industrial lands to increase productivity. For the first time it also provided the opportunity to anticipate reasonable returns on investment in forest management.

As the forest managers of inland northern California became more involved in intensive forest management it became apparent that much of the critical data needed to manage effectively were not available. We really did not have any yield information that would indicate the potential for our existing stands, nor did we have any way of projecting how our various management activities were going to affect the yield. The prodominately mixed conifer lands of the region were of particular concern.

In 1976 Professor Lee Wensel proposed that the industry join in a cooperative with the University of California, Department of Forestry, in attacking the problem. The problems of such a long range project were so overwhelming that it took almost two years to convince ourselves that we should commit to the project.

Seven years later we have accomplished our original goal with **CACTOS**, the CAlifornia Conifer Timber Output Simulator, up and running. The cooperative is now planning future studies which will enhance the reliability and utility of **CACTOS**. There is every reason to believe that it will be a successful effort.

The Northern California Forest Yield Cooperative has been an outstanding example of what can be accomplished when the efforts of Academe, Industry, and the State and Federal agencies are focused on a problem.

Robert Leatherman

Preface

Reliable growth projections are critical to forest management planning. Predictions of how forest stands will develop under alternative management prescriptions are used in selecting the combination of treatments (harvests, thinnings, plantings, weeding, controlled burns, etc.) that will produce the maximum return on investment. Given information on management costs and stand response, mathematical models exist for solving this optimization problem. However, information on management costs is not readily available and existing stand response models are outdated.

The research reported here attempted to develop a model for projecting the growth of conifer forest stands in northern California, with or without hardwood competition. Using this model forest managers will be able to test alternative management options and make intelligent choices between options.

Although the work has been directed from Berkeley, this research has been made possible by the active participation of many people throughout northern California. In the nine years since the project was first proposed, we have had the financial support from our University Department Chairmen, Rudy Grah, John Helms, and Dennis Teeguarden. They believed in this work and actively supported it with McIntire-Stennis federal research funds. The many industry cooperators cited in the text also believed in the project, enough so that they committed money to the project at a time when the timber industry was in difficult financial straits. Their contributions of the industry cooperators cannot be measured in money alone. They regularly attended planning meetings, did time consuming field work, and reviewed the work to provide valuable suggestions on the overall direction of the work as well as reviewing the technical details.

Finally, it has been a pleasure to work with the various students and ex-students who have worked on this project. The work has been an important part of their education. Their dedication to the tedious details of digitizing tree rings, editting field data records, and computer programming has made this project possible.

While completion of version 2.0 of the **CACTOS** system represents an important milestone in this project, the work is far from over. There are still many data to be analyzed for better estimates of productive capacity, birth and death rates, and growth rates. Also, continued monitoring of established field plots will lead to better response information for partial cuttings.

It is our hope that the present group of industry cooperatorts will be joined by additional industry cooperators, state and federal agencies, and other university researchers. Their cooperative spirit developed in the conduct of this work should continue and serve as a model for other groups. Truly it has been a pleasure to work with this group.

Lee C. Wensel

Greg S. Biging

CONTENTS

INTRODUCTION

The purpose of this paper is to describe the development of the Northern California Forest Yield Cooperative, to summarize its research results, and to focus on the current status and future prospects of the project. The purpose of the cooperative is to collect the mensurational data necessary to develop forest growth and yield models to assist foresters in managing the young growth conifer forests of California.

Getting started

The Northern California Forest Yield Cooperative came into being on September 29, 1978 with the agreement of eight companies to support growth and yield research at the University with both funds and personal effort. These cooperators were soon joined by four more companies, making a total of twelve industry cooperators representing approximately two million acres of private industrial forest land in northern California. The proportion of the ownership in each of the twelve industrial ownerships is illustrated in Figure 1.

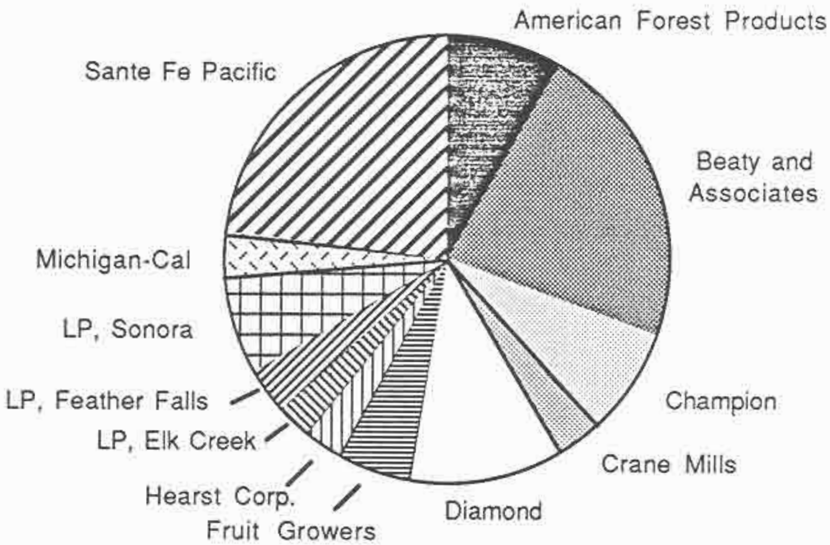

Figure 1. Proportion of area by industrial ownership

These industry cooperators were subsequently joined by representatives from the Soil Conservation Service and the University's Blodgett Research Forest. At the request of the members, the California Forest Protective Association served as an intermediary for collecting funds from the membership and forwarding them to the University. The California Department of Forestry (CDF) was represented at several of the meetings. While CDF did not support the project financially, their representatives agreed to supply inventory data from the State Forests, if it would be of use to the project. Representatives from the U.S. Forest Service, who were beginning a similar project in the Sierra, attended several of the early meetings.

Professor Lee C. Wensel and Specialist Bruce Krumland were working on a similar cooperative growth and yield project with several forestry companies in California's north coast redwood area. The Redwood Cooperative, begun in 1974, served as a model for the Northern California Forest Yield Cooperative. Wensel and Krumland used their experience in this cooperative to promote the new cooperative.

To discuss the prospects of a new cooperative, representatives from five forest industry companies met with Lee Wensel and Bruce Krumland at an informal meeting held in Berkeley in December 1976. Subsequently, John Black of the Santa Fe Pacific Timber Co. assisted in organizing another meeting in Anderson, California in March of 1977 where approximately 30 industry representatives met with Wensel and Krumland.

Principal topics at the meeting included a discussion of the organization and administration of the Redwood Cooperative, the progress of this work, and how results were to be used in a forest management situation. It was recognized that the stand conditions and management situations were not the same in the interior as they are on the north coast and that the redwood models would not apply directly. Also, concern was expressed as to whether a common denominator for the project objectives could be reached and, if so, whether or not such common objectives would be specific enough to justify each company's participation. The tentative cooperators were each visited

(1) to gain a sense of their operational situations,

(2) to survey their specific objectives, and

(3) to appraise the quality and extent of existing growth plot data.

As a result of these visits, specific objectives for growth models were formulated, together with proposed organizational and development plans.

Though there was much interest, there was also much doubt as potential cooperators worried about the likely success of the project, the cost of any commitment, and the implications of sharing the forest inventory records with competitors -- or with government agencies. Others were worried about contributing to a University research project where all of the results would eventually be made public and be free to non-cooperators as well as cooperators.

Under the leadership of **Bob Leatherman** (Champion International), the industry cooperators realized that the task of developing growth and yield models for northern California conifers was too large a job for any one company. Further, since the results of the Redwood Forest Yield Cooperative were becoming available, there was reason to believe that the University research team would be successful. Thus the Northern California Forest Yield Cooperative (NCFYC) was created.

Support

The forms of the industrial support to the project are illustrated in **Figure 2**. The industry cooperators assessed themselves to raise money to donate funds to the University to help support their growth and yield research work. Further, they agreed to provide technical assistance in planning and to do most of the necessary field work. The industry representatives who participated in the planning and execution of the various tasks in the project are given in **Table 1**.

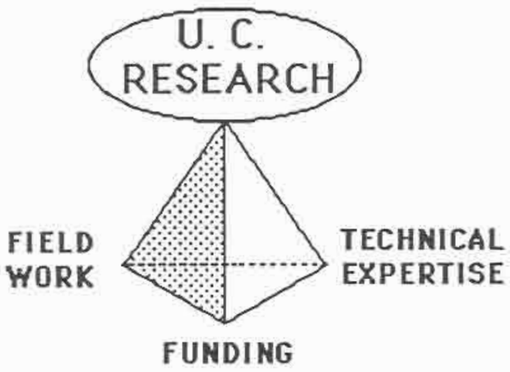

Figure 2. Industrial support of cooperative research.

Direct funding for the project came from federal McIntire-Stennis forestry research funds, University funds, as well as the gifts from the cooperators. The majority of the field work was provided by the individual cooperators on whose lands the measurements were taken.

Staffing

On the University side (**Table 2**), Professor **Lee C. Wensel** is the project leader, assisted by Professor **Greg S. Biging** who joined the Berkeley faculty in spring 1978. **Bruce Krumland**, then a staff researcher and PhD student doing redwood / Douglas-fir growth and yield research under Professor Wensel, assisted in the early planning of the new cooperative. In addition, funds from the industry cooperators supported a full time staff position held initially by **Robin Filion**, followed by **Jim Koehler** ~~and~~ **Peter Daugherty**. Each of these men had worked part time for Professor Wensel prior to joining the project full time. The project also provided part-time employment for a number of graduate and undergraduate students who worked on the project while attending classes (**Table 2**).

Table 1. Industry representatives[1], Northern California Forest Yield Cooperative

American Forest Products Co.[2]
- Dan Barringer
- John Pricer
- Les Rohssler

Bendix Forest Products Co.[2]

William Beaty and Associates
- William Beaty
- Bob Manning
- Marty Patton

Champion International Corporation
- Alan Hunter
- Bob Leatherman (chair 1978 - 80)
- Jeff Madsen
- Dave Marshall
- Gary Nakamura (chair 1983 - present)

Crane Mills
- Frank Barron
- Bob Crane
- Roy Henson
- Bob Hughes

Diamond Lands
- Bill Orme

Fruit Growers Supply Company[3]
- Charles Brown
- Nick Freemyers

The Hearst Corporation
- Duncan Brinkerhoff

International Paper Company[3]
- Jheri Donchin
- Greg Johnson
- Brian Merryman
- Tim White

Louisiana Pacific (Elk Creek Division)
- Mike Johnson

Louisiana Pacific (Feather Falls Division)
- Jim Cohoon
- Scott Koehler
- Gordon Ross
- Randy Vasquez

Louisiana Pacific (Sonora Division)
- Will Dorrell
- Kathi Hoertling
- Leon Manich
- Bill Snyder

Michigan-California Lumber Company
- Henry Alden
- Janice Davenport
- Cliff Kennedy

Sante Fe Pacific Timber Company[4]
- Dean Angelides
- David Bischel
- John Black
- Scott Hall
- Jim Mehrwein
- Stuart Smith
- Art Stackhouse (chair 1980-83)
- David Volkmann

---

1 Individuals listed were employed by the member companies at the time of their participation.

2 The Martell Division of Bendix Forest Products was sold to American Forest Products in 1981. With this sale the remaining Foresthill Division of Bendix dropped out of the cooperative. Data from both companies are included in the study and are represented in the figures for American Forest Products.

3 With the sale of International Paper's California timberlands, Fruit Growers Supply, Ltd. assumed the IP membership.

4 Name changed in 1984 from Southern Pacific Land Company.

Table 2. Non-industry representatives, Northern California Forest Yield Cooperative

University of California

Department of Forestry and Resource Management

Faculty
Greg Biging (co-director)
John Helms
Lee Wensel (director)
Paul Zinke[1]

Staff Researcher
Peter Daugherty (1984 - present)[3]
Robin Filion (1978 - 82)[3]
Jim Koehler (1982-84, 84-present)[3]
Bruce Krumland[6]

Other[1]
Jim Bertenshaw
Martha Fox
Jibe Igdopipe
Al Stangenberger
Robert Standiford

Students
Ken Brown[2]
John Conroy[4]
Doug Fraser
Jeremy Fried
Jerry Ingersoll
Jon Jue
Vaughan Landrum
Walter Meerschaert[4]
Robert Miller
Ed Peggs
Eugena Wong Seito
Mark Teply[4]
Paul Van Deusen[5]

Blodgett Forest
Bob Heald
Scott Holmen

Cooperative Extension
Tom Robson
Pete Passof
Rick Standiford

Others

Cooperative Forest Protective Association
Bruce Bayless
Fred Landenberger

Soil Conservation Service
Jack Bramhall
Sherman Finch

Notes:
1 Analyzed soil and vegetation samples.
2 Now employed by Sante Fe Pacific Timber Co.
3 Full time staff researcher, employed part-time while students.
4 Graduate student while working part-time on project.
5 Employed while a PhD student; now with the U. S. Forest Service, New Orleans.
6 Assisted in early planning efforts; co-author of CRYPTOS (the redwood / Douglas-fir model).

OBJECTIVES

Generally stated, the objective of the University's growth and yield project was to develop a computerized model to predict the growth and development of young-growth stands of conifer trees in northern California. The forest types represented include the Douglas-fir, ponderosa pine, true fir, and mixed-conifer types. Though the concern of the project was to provide growth predictions for conifer stands in northern California, as a practical point, interest focused on the areas in and around the ownerships of the twelve cooperators who would be providing data for the estimation process. As shown in **Figure 3** this region begins in Toulumne County, continues north along the foothills of the Sierra to Shasta County, across the southern Cascades, then east across the Shasta-Trinity area, then touching the eastern side of the Mendocino Range. The areas covered by this study adjoin the National Forests where two U.S. Forest Service studies of growth and yield are being conducted, one in southern Oregon and northeastern California and the other consists of the 6 National Forests from the Plumas to the Sierra.

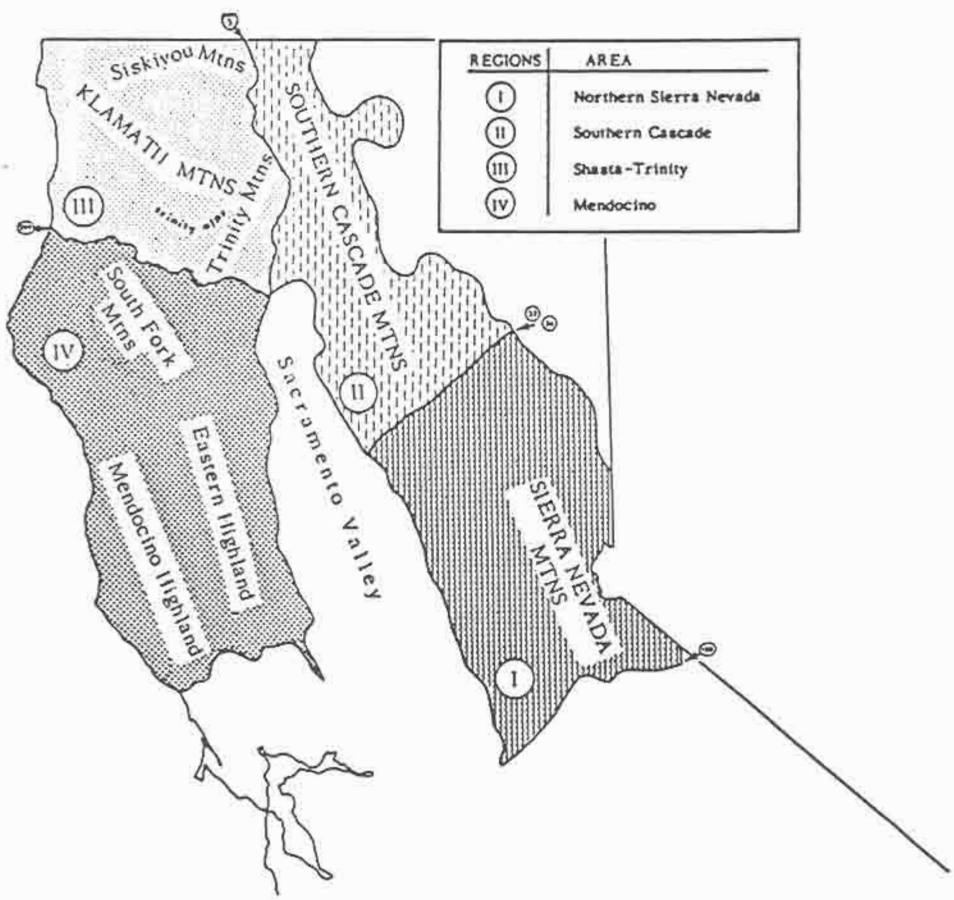

Figure 3. Study regions for Northern California Forest Yield Cooperative

After meeting individually with forest managers, the requirements for a computerized growth model appeared to center on the following overlapping themes:

(1) Growth and yield models developed should be capable of being applied to specific on-the-ground stands or tracts of timber. (Operationally, actual inventory figures would be used as input to define the stand for which a growth prediction is being made.)

(2) Models should be amenable to predicting the response of specific stands and time flow of timber products resulting from specific management prescriptions (e.g., timing, intensity, and character of partial harvest).

(3) The models should be capable of updating inventories to a common point in time. This has the advantage of immediate cost savings in the form of increased time between inventories or decreased measurement efforts.

(4) The same basic growth model should be capable of accepting a wide range of input information at varying levels of resolution. Flexible input data requirements of the models should allow growth predictions for stands that are incompletely described (i.e., with missing tree heights or missing crown measurements).

(5) The models should be capable of providing the information necessary for economic analysis and the input coefficients for large scale forest planning.

These themes outline three major concerns of the potential users of the computerized growth and yield model. First, they were concerned about their ability to use the computer model once it was finished. If, for example, the model required information that they could not supply in the normal course of doing business, it would be useless -- regardless of the elegance or accuracy of the predictions. Second, they saw the need for various levels of predictions based upon varying degrees of specificity. Updating inventories would require accurate tree-by-tree predictions whereas general management planning may only require accuracy on a stand-by-stand basis. Third, the forest managers surveyed wanted to be able to use the program to produce the types of data summaries to which they were accustomed. This included yield summaries for economic analyses of various management strategies.

These themes are summarized into three general objectives to insure utility of the computerized growth and yield model:

(1) Industry-standard data input and management options -- the model should be based upon variables that the manager will be able to supply and should allow the types of stand manipulations commonly used in the field;

(2) Flexible data input requirements -- the model should allow growth predictions with general stand information as well as complete tree information; and

(3) Flexible display of output -- provision should be made for a variety of alternative output formats and summary reports.

These general objectives do not reflect the more specific tasks that had to be accomplished to produce the estimates desired. These tasks included a major programming effort to build and refine a growth and yield simulator and a series of basic mensurational studies as outlined in the next section. The results of these efforts are described in the sections that follow.

Participation by industry members

In addition to aiding in the development of a plan for doing the necessary research, the forest managers also recognized the need for their continued and detailed involvement in the project. This involvement was both to assist in the conduct of the work and also served to develop a common understanding of the needs of the industry as a whole and to help focus the research effort to meet those needs. Thus, representatives of all twelve member companies have attended the periodic planning meetings of the cooperative, reviewed drafts of objectives, field instructions, manuscripts, and in general supported the University research effort. As a major contribution, the member companies collected the majority of the field data used in the analyses.

As work progressed, committees of the cooperators were set up to advise the University research team on the following topics:

(1) INPUT -- What specific information will be available for entry when one wants to use the model? [Art Stackhouse, Gary Nakamura, and Jim Cohoon]

(2) OUTPUT -- What form should the output be in (units, labels for columns and rows, etc)? [David Volkmann, Jheri Donchin, Bob Heald, Duncan Brinkerhoff, and Kathi Hoertling]

(3) HARVEST -- What alternative harvesting criteria need to be implemented? [Dean Angelides, Randy Vasquez, and Henry Alden]

(4) SITE QUALITY -- How will "site" measures be expressed, for what areas, and how will they be related to the internal workings of the growth model? [Gary Nakamura, Duncan Brinkerhoff, Bob Heald, Art Stackhouse, and Kathi Hoertling]

The specific technical contributions of these committees to the research effort are cited in the sections that follow.

DATA

The first major project of the cooperative was to assess the availability of data for use in producing growth estimates. This was started even before the cooperative was officially formed and continued until an assessment was made for each of the twelve cooperators. The results of this survey showed that existing data were inadequate for developing a growth model. First, for the growth plots that did exist, most of them did not have complete measurements of tree diameters, total heights, and crown ratio (or height to the base of the live crown). Second, the measurement standards for the plots were not of uniformly high quality. Finally, the distribution of the existing plots over available timber types, elevations, site qualities, and other attributes was inadequate to represent the area covered by the study.

Thus, to overcome the shortcomings in the existing data, the principal data sources come from the stem analysis and permanent plot measurements taken as part of this study. However, the first published results of this project came from the coop-supplied measurement on trees felled as part of the tarif study.

Tarif data

For the purpose of developing tarif access tables for cubic volume, fourteen companies in northern California plus the U.S. Forest Service collected data from 458 trees felled on temporary plots and 1353 dendrometered trees between 1975 and 1977. The industry cooperators (many of whom participated in the tarif study) felt that they had considerable investment in these data, but that the data had not been adequately analyzed nor had volume tables been produced from the initial study. Thus, they requested that the Berkeley staff analyze the tarif data to develop volume and taper relationships for the six major mixed conifer species. These data were presented to the Berkeley staff in the fall of 1979 and Greg Biging led the work of developing taper and volume equations for the six major mixed conifer species. The results of this research are given in Research Note No. 2 **(Biging 1981)**. These volume tables and taper equations were used by the cooperators in the interim period from 1981 to 1983 before the stem analysis data were available for developing new volume and taper equations.

The volume and taper equations developed using the tarif data were superceded by those produced using the stem analysis data (below). This was because the tarif data lacked height and diameter measurements above the merchantable top and because only minimal stand information was collected at the time the trees were felled. Thus, unlike the stem analysis data the tarif data could not provide complete tree profile information. Additionally, the tarif data could not be used to obtain recent height growth information nor could it be used to investigate the effect of stand density on individual tree growth.

Coop permanent plots

A coop-wide sample design was constructed to locate permanent plots in a manner that better represented the ownership, with the individual cooperators being responsible for establishing, measuring, and maintaining the plots. As a result, a total of 710 permanent plots were established, most of which coincide with the locations of previously-established industry plots. The distribution of permanent plots by company is given in **Figure 4**. Comparing the sample distribution in **Figure 4** with the ownership proportions in **Figure 2** shows that the number of plots in the permanent plot data base is not proportional to the areas represented by the cooperators' land holdings. Initially, we requested 50 plots per company distributed over the various timber types, site index classes, and stocking levels that predominated on each ownership. For several companies this number was increased to adequately represent the types present, especially when a company had a number of unique vegetation classes not present on adjacent ownerships.

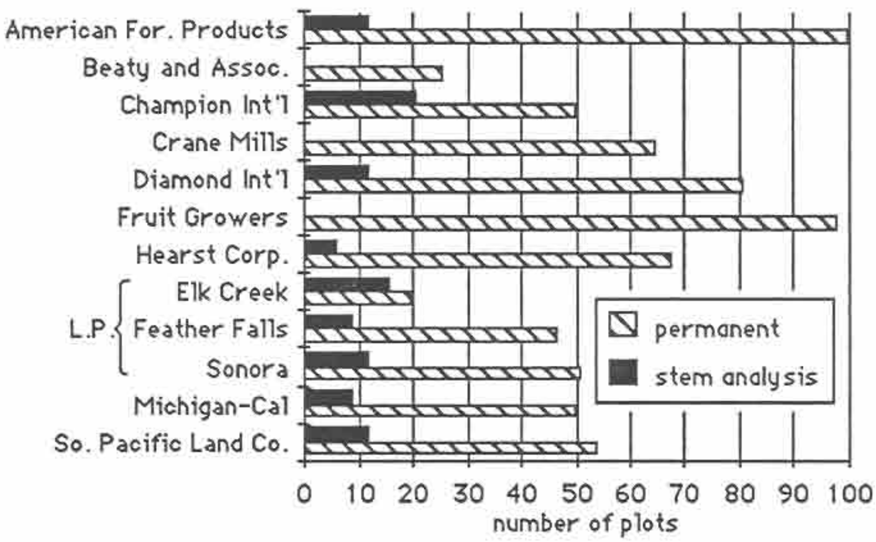

Figure 4. Numbers of research plots by ownership.

For the four regions shown in **Figure 3**, **Figure 5** shows the number of permanent plots for each timber type. Region 1 was the most heavily sampled, with the mixed-conifer type predominating. (Here mixed conifer simply means that the stand is at least 80% conifer and neither ponderosa pine, Douglas-fir, nor true fir make up 80% of the stand by basal area.) The numbers of plots by stocking levels are illustrated in **Figure 6**. Note that the first four stocking classes are represented in all of the timber types and that the most dense class is not well represented in either the ponderosa pine or Douglas-fir types. These two species did occur in denser stands in the mixed conifer type, however.

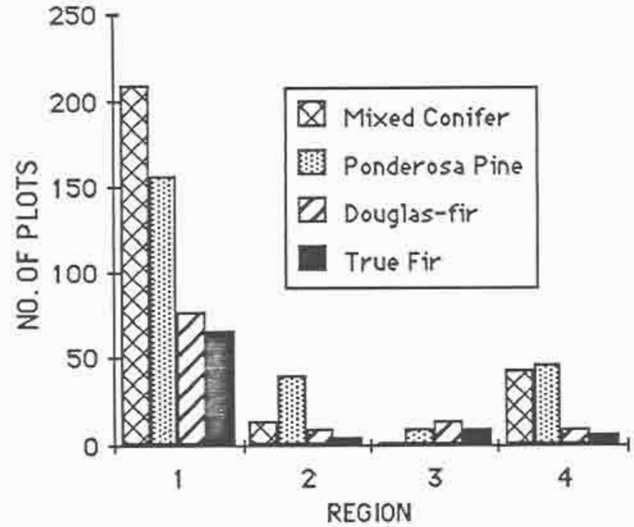

Figure 5. Numbers of permanent plots by region for each timber type.

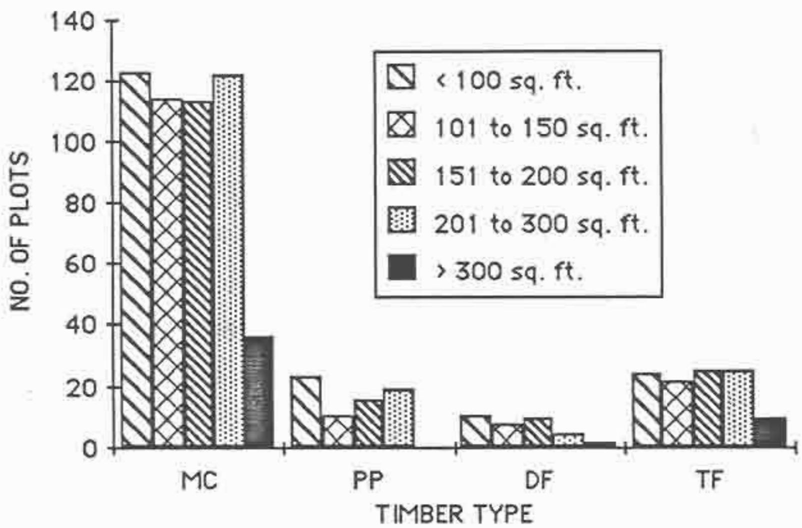

Figure 6. Numbers of permanent plots by timber type and stocking level.

Measurement standards were established and agreed upon by the cooperators so that data obtained from these permanent plots could be combined. Also, the cooperators agreed to use these same standards when measuring their other permanent plots (although height and height to the crown base was not necessarily taken on all non-Coop plots because of the added measurement cost involved).

While each of the cooperators intended to obtain measurements to the same standards, some deviations do exist. For some companies the coop plots were placed at the same locations as previously measured plots. In these cases the previous plot size was adopted for the coop study. Also, some differences appeared in minimum diameters measured for a few of the cooperators. Differences also exist in the way tree heights and heights to the crown base were measured. Differences in the plot definitions are not serious but differences in the measurement procedures will have to be ferreted out and corrections made at the time of the remeasurement. The most important of the missing variables appears to be the age and height measurements for site index trees. For making growth projections the site index of each species present on the plot is required.

The number of prior measurements available for the trees on the permanent plots varies from none (for the plots established in 1979 or 1980) to as many as five. Unfortunately, few of the prior measurements include tree height and height to the crown base.

The permanent plots are now being remeasured with several companies having completed the remeasurement. The remeasurement data will be collected in Berkeley and added to the database to permit the reestimation of the growth equations computed first using the stem analysis data.

Stem analysis

Since it was apparent that the permanent plots would not yield reliable growth estimates until after the second or third measurement, and because a sample of trees was needed to develop stem and crown taper models and site index curves, a separate stem analysis study was proposed.

A preliminary stem analysis procedure was developed and field tested at Blodgett Forest Research Station in the fall of 1979. As a result of the field test, the procedures were revised. Retesting was done in the winter of 1979/80 by the Berkeley staff and Champion International Corporation. Further refinements were incorporated and a final procedure for conducting stem analysis was distributed (**Biging 1980**). At the Spring meeting of the cooperative in May of 1980, the stand type and the site categories were defined. At that time, the allocation of sample cluster categories were made to participating companies.

In the summer and fall of 1980 Robin Filion and Greg Biging visited the nine cooperators who elected to conduct this research and to brief each cooperator on the procedure. To ensure consistency and completeness in the field measurements they assisted the field crews in the establishment of a three plot cluster, and aided in the measurement of trees on the plot, felling, sectioning, photographing rounds, and collection of foliar information. After the successful establishment and measurement of a cluster, each company took primary responsibility for the measurement of their remaining stem analysis plots.

The Berkeley staff monitored the progress of the stem analysis work and collected the processed film used to photograph the tree sections and the breast height sections, tip cuts and foliar samples that were to be analyzed in the laboratory. As the data were collected, copies of the field forms were sent to Berkeley for keypunching and verification. At the same time the photographs of the sections were being digitized to produce diameter inside and outside bark and annual radial growth measurements from the pith to the outer rings (**Biging and Wensel 1984**). To produce these measurements on over 8000 sections and 3000 tip cuts, a number of undergraduate students (**Table 2**) were employed to digitize the annual location of tree rings on each photograph using equipment at the Space Sciences Laboratory in Berkeley and to hand measure growth and size for the tip cuts. These time-consuming measurements took until mid-1982 to complete. These data were then edited and entered into a computerized data base, referred to as the stem analysis data base, and were verified and made available for analysis in the fall of 1983 (see below).

A total of 39 stem analysis clusters, containing 109 plots, were established by the industry cooperators. The numbers of stem analysis plots taken by each company are illustrated in **Figure 4** while the distribution of trees by region is illustrated in **Figure 7.** As shown in **Figure 8**, the most prevalent species in the stem analysis samples is white fir, followed, in order, by ponderosa pine, and Douglas-fir.

In future studies, these data will be used, among other things, to develop improved estimates of site productivity, to examine the relation of soil and foliar nutrient levels to individual tree growth, and to examine the wood quality characteristics of young-growth trees as related to stand and tree characteristics.

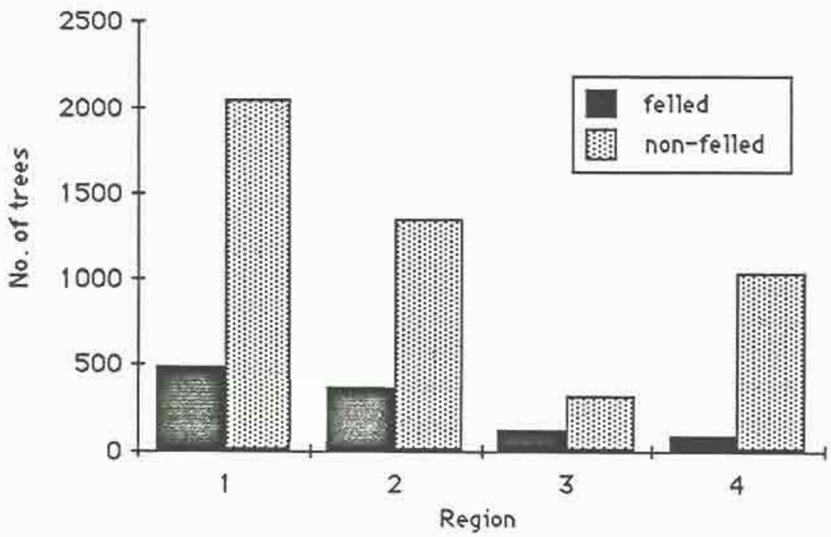

Figure 7. Numbers of trees by region in stem analysis sample.

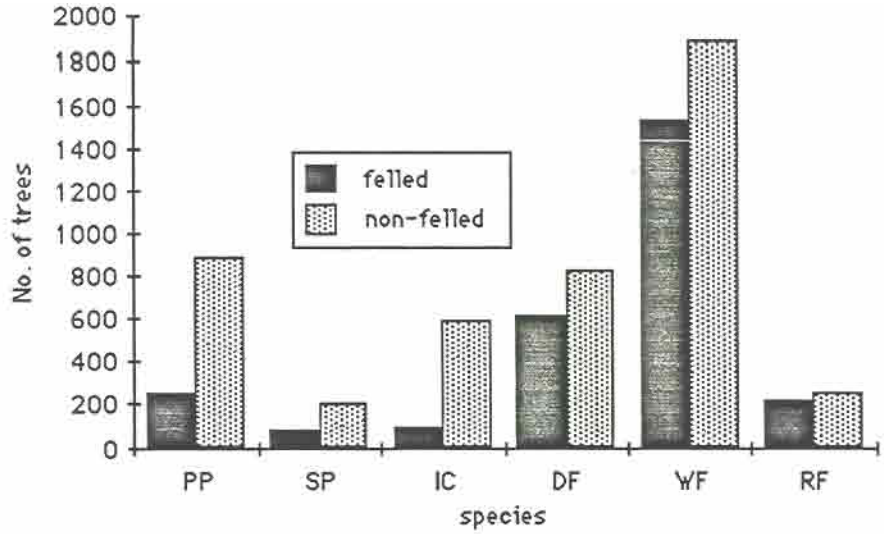

Figure 8. Numbers of trees by species in stem analysis sample.

As with the permanent plots, the distribution of the stem analysis sample is not in proportion to the size of each company's holdings. Rather, the stem analysis study was designed to represent, the range of conditions judged to be central and critical to the project. Thus, while more detailed, the stem analysis data are less representative than the permanent plot data.

To date, the stem analysis data base has been the primary data source. It has been used for the development of taper and volume relationships, site indices, crown volume and dimensional relationships, and diameter and height growth models.

Soils and foliar analysis

As part of the stem analysis project conducted during the 1980 and 1981 field seasons, a study of soil and foliar nutrients was undertaken at the stem analysis cluster locations as a supplement to the traditional stem analysis measurements. The foliar nutrient study was designed by **Professor Paul Zinke** and the soil study was jointly developed by **Paul Zinke** and **Gary Nakamura** (chairman of the Soils committee), in cooperation with **Wensel and Biging**.

For the foliage study, samples of the current year's foliage and the prior year's foliage were collected for a randomly selected felled dominant of each species present at the plot locations. Plot samples were combined into a cluster sample for each species. Under the direction of **Professor Zinke**, the foliage samples were analyzed for iron, magnesium, manganese, nitrogen, phosphorus, potassium, sodium, and zinc content by "atomic absorption spectrophotometry" and other techniques.

The soils study was not formally part of the stem analysis study at the time of its proposal, but negotiations were undertaken with the Soil Conservation Service (SCS) to assist the cooperative in this regard. In December of 1980 State Conservationist **Francis Lum** agreed to participate by having SCS personnel gather the soil information for the 30 clusters that were proposed. However, it was not until early in 1982 that a formal proposal for soil sampling was developed. The research design called for one representative soil profile to be described and sampled by SCS and five satellite soils samples to be collected from the cluster area to evaluate soil variability. The profile description included soil depth, color, texture, structure, coarse fragments, pH, degree of horizonation, roots and pores, and general site characteristics of slope, aspect, elevation, and climatic regime. Soil samples included one two quart sample per horizon with 3 samples from the surface 12 inches and 2 samples from the 12 to 48 inch depth. Additionally, bulk density samples were collected for each horizon. The satellite samples included 5 additional samples from the cluster area taken to evaluate site variability. Each satellite sample consisted of five subsamples from the 7 to 9 inch depth.

From May to June of 1982 SCS collected the soil samples and data specified in the research proposal. The collection of the soil samples from the participating companies was handled by **Sherman Finch** of the Davis office and **Jack Bramhall** of the Red Bluff office of SCS. Samples were tagged and brought to Berkeley for analysis by **Paul Zinke**'s research staff.

The foliar nutrient analysis is essentially completed with the exception of some minor species such as incense cedar. The soils analysis is also completed with the exception of the determination of soil moisture storage capacity.

Future research work includes the statistical analysis of the influence of soils nutrients, foliar nutrients, and the interaction of soil and foliar nutrient status on tree growth. Additional research will include the development of improved estimates of land productivity measures since site index does not explicitly take into account the nutrient status of the site, nor the physical composition of the soil. This research will seek to relate the physical and chemical properties of soil to the productive capacity of the land. This in turn will be useful when assessing the productivity potential of land in the absence of trees and will increase the precision of the growth models by improving estimates of land productivity.

Development of data base systems

As discussed in the previous sections, there are two major data sets developed as part of this project -- the first from permanent plots and the second from stem analysis. Because of the size and complexity of these data sets, a data base management system was used to store and organize the data for analysis. This system, called SIR (for Scientific Information Retrieval (**Robinson and others, 1980**), operates on the University's IBM 3081 computer. SIR was used to develop separate data bases for the permanent plot and the stem analysis data sets. A data base, for our purposes, can be defined as a group of data records, each containing separate data items, and having a well-defined relationship between the types of records so that the information can be retrieved for analysis.

The purpose here is to give a brief overview of the features and structure of the SIR system and to outline its importance in our growth estimation work.

Features

The SIR program provides a variety of tools for entering data items as well as modifying (editing), deleting, updating, and retrieving data from a data base. Upon entering data, a number of verification features assist the user in detecting unreasonable data items. For example, one can examine rates of taper, ranges of diameters and heights, and radial growth rates. Invalid and out-of-range values are placed into an error file for inspection. During this process it is common to recheck original field sheets or, on occasion, to remeasure the tree or section.

Structure

SIR allows the user to establish hierarchical or network relationships between groups of data items. The actual description of the data relationships is referred to as a schema definition. As illustrated for the stem analysis data base in Table 3, our data bases are hierarchical in structure, typified by clusters, plots within clusters, trees within plots, and cross-sections within trees. This structure permits efficient retrieval of data at any level.

Table 3. Four levels of data in the stem analysis data base.

Level	Information
cluster	density, volume and growth summary, region and foliar information
plot within cluster	elevation, slope, aspect, location, site index
tree within plot	species, DBH, total height, live crown ratio
section within tree	diameter, age, and diameter growth rate, height at which section was cut from tree

Retrievals and reports

Data can be drawn from the data bases by SIR's powerful retrieval structure. Data retrieval is accomplished by writing a retrieval program with the SIR language and editor. This SIR program can take into account the structure of the data base and the hierachical nature of the data to locate the subsets of interest. Commands are written to draw data items from various places in the data base, perform logical or arithmetic functions on them, and store them in a data file for analysis by standard statistical programs. This direct interfacing capability of SIR makes it relatively easy to perform statistical analyses over any portion of the data set. Alternatively, SIR has a report generator that will layout report tables and provide summary statistics for variables of interest.

The SIR system also provides protection of the integrity of the data files. Confidential data can be protected by passwords so that only authorized users have access to sensitive data.

ANALYSIS

The previous section outlines our efforts to develop data bases to enable us to define the various relationships needed to develop a growth simulator. The simulation programs are presented in the next chapter while this section summarizes the statistical analyses used to develop mathematical equations to express volume and taper relationships, site index, crown shape and size, and tree diameter and height growth rates. Further information on these topics can be found in the Research Notes that are cited below.

The symbols used to express the variables and relationships are summarized in **Appendix A**, as well as being defined as they are used in the following sections.

Volume and taper relationships

As an important component of **CACTOS**, whole tree volume equations for the mixed conifer species were needed to provide summary information on current size and growth (cubic and board foot volume and volume growth for a specified merchantable top) on stands and trees. Taper equations were also needed to calculate standing log inventory to provide information on the number and volume of logs by diameter classes and species. As an important by-product, volume tables for young-growth trees were desired.

Analysis of the profile data for the six major conifer species from the stem analysis data base was begun in the summer of 1982. In this study, a taper model was derived and compared in accuracy with a more complex model reported in the literature as being a superior choice for a taper equation. There were some differences in accuracy between the models, but overall they performed quite similarly. Volumes predicted with the taper-based system formed the basis of young-growth volume tables and were compared with scaled volumes. The predicted cubic volumes were within 3 percent of scaled volumes and the board foot volumes were within 7 percent.

Whole tree volume equations, which predict total tree volume as a function of diameter and height, were also developed for the six conifer species. The volumes predicted with the whole tree equations were also compared to scaled volumes. With minor exception these predictions were quite similar to the volumes predicted by using the taper equation.

The volume equations and coefficients are reported in Research Note No. 7 **(Biging 1983)** and the analysis techniques used are given by **Biging (1984a)** The taper and whole tree volume equations developed are used in **CACTOS** to estimate tree and log volumes as well as to develop the log report, and the number of logs by size.

Site index

One of the major objectives of the design of the stem analysis data base was to obtain height-over-age curves, depicted in **Figure 9,** for site trees so that young-growth site indices could be developed. Site index was also needed as an important independent variable in many of the predictive equations in **CACTOS**.

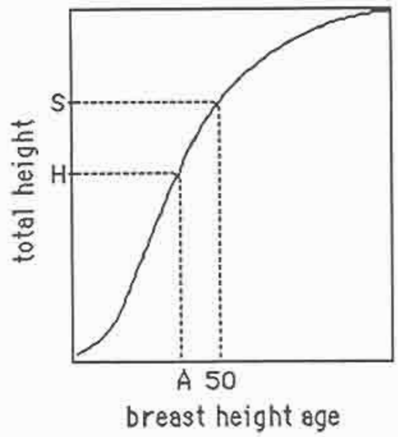

Figure 9. Illustration of 50-year breast height age site index (S) for tree with height (H) and breast-height age (A).

On the stem analysis plots four to six trees (two to three dominant or codominant trees for each of the two most prevalent species in the overstory by basal area) were selected randomly as site index trees. These trees were selected to have minimal past damage to tops and minimal height growth reductions due to extremes in density. Of the 1039 trees felled, 343 site trees (198 in the mixed conifer type) were available for analysis that were at least 40 years in age.

Initial site index curves prepared by Greg Biging in 1982 only used the 198 site index trees from the mixed conifer forest type. These curves appeared to underpredict height development at the more advanced ages (80-100). For this reason a re-analysis of all 343 site index trees was conducted using a different mathematical model. In this model each tree was individually modelled for height growth using a Chapman-Richards function (**Pienaar and Turnbull 1972**). The coefficients from the individual tree models were averaged to form the average height growth pattern of site index trees. Comparisons of curves fit for the individual species showed similar trajectories for all species. Thus, all species were combined for the final curves. The resulting site index curves have a base age of fifty years at breast height and are applicable in the range of 20 to 100 years. These newer curves better predict height development than did the earlier curves.

Comparing the new curves to the young-growth curves of **Dunning and Reineke (1933)**, which use total age as a base, it is evident that the two sets of indices are similar especially on the higher sites. At ages below index age it appears that the new curves predict lower heights than Dunning and Reineke's curves especially on sites lower than 60. On the higher sites (100 and above) the new curves are lower than Dunning and Reineke's curves beyond age 70. However, since it is suspected that Dunning and Reineke's curves overpredict on higher sites at advanced ages, the earlier leveling off in the new curves is accepted by the cooperative.

The new site index curves are given in Research Note No. 8 **(Biging and Wensel 1984)** and the methods used are given by **Biging (1984b).**

During the July 10, 1984 meeting in Berkeley the coop moved to adopt the use of the new site index curves. These curves are being used in **CACTOS** as a basis for predicting potential height growth.

Crown models

In order to compute the tree and stand competition measures used in the growth estimators (below), tree crown profile information was obtained from over one thousand trees felled as part of the stem analysis project. Up to five measurements of crown diameter were taken at log lengths (every 16.5 feet) and at the 5-, 10-, and 15-year tip cut locations. These measurements formed the basis for development of models to predict crown width at any point (crown profile) and crown volume. Crown volume for each tree was computed as the average of the left and right radial crown volumes computed with Smalian's formula using radial crown measurements from the left and right sides of the felled trees. The crown volume and area equations are given in Research Note No. 9 by **Van Deusen and Biging, 1984.**

As shown in **Figure 10**, the crown cross sectional area (CA) is computed as a function of the height above ground (h) as well as total height (H) and height to the crown base (HCB).

The expressions for crown area (CA) and crown volume (CV) are used to develop the measures of competition for each tree in the stand. Another competition measure that uses the cross sectional area of the crown at 66% of a tree's height (CC_{66}), computed by summing the crown area of all trees in the stand at the height h = 0.66H of the subject tree. Trees that have 0.66H below the base of the live crown are evaluated at the base of the live crown. This is illustrated in **Figure 11**

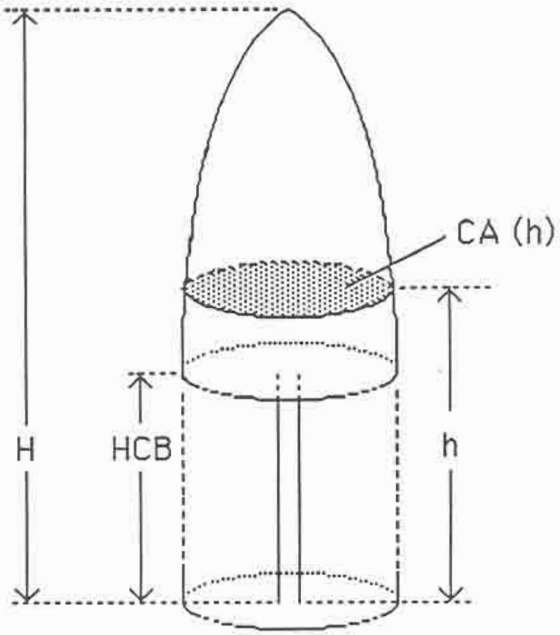

Figure 10. Crown models for cross sectional area (CA) as a function of the height above ground (h).

where the values of CC_{66} are illustrated for the trees shaded. In (a), the center tree is shorter than the others, giving it a higher value of CC_{66} than for the left tree in (b) or the right tree in (c). Note that, as measured by CC_{66}, the center tree contributes nothing to the crown competition for the tallest tree shown in (c). The computational process for computing CC_{66} from CA(h, H, HCB) is given in Research Note No. 12 (**Wensel and Koehler 1985**).

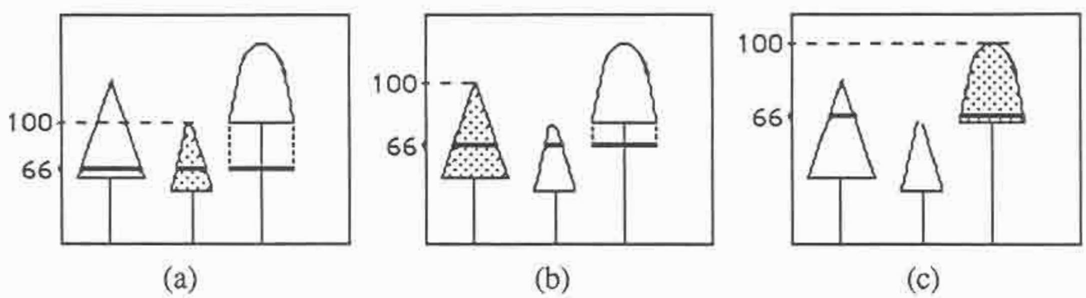

Figure 11. Crown cross sectional area at 66% of tree's height. (CC_{66} shown by bold line for shaded tree.)

Growth functions

At the heart of the cooperative research project is the development of tree growth prediction equations for use in **CACTOS**, the CAlifornia Conifer Timber Output Simulator (**Wensel and Daugherty, 1984**). These growth prediction equations are constrained by the information available to the user. These include S, the 50-year site index (**Biging and Wensel, 1984b**) for each species in the stand and the following items for each tree (all symbols used are summarized in **Appendix A**):

symbol	definition
sp	species
DBH	diameter at breast height
H	tree total height
HCB	height to the crown base
TPA	trees per acre

The list of these variables for each tree in the stand is referred to as the tree list. Expressions to be used in predicting growth rates are restricted to be functions of these variables. (Frequently tree height (H) and height to the crown base (HCB) are not available for all trees. If this is the case, the **STAG** program discussed below can be used to supply estimates of these quantities before the growth simulation process begins.)

In the individual tree modelling approach used here, tree growth is modelled as the product of two components: potential growth and a competition factor that expresses the ability of the tree to reach its potential. That is,

growth = (potential growth) x (competition)

or

$$\text{growth} = P \times C$$

where P and C are mathematical expressions of the potential growth and competition, respectively.

Height growth

For height growth, the estimated height growth (G_H) is expressed as

$$G_H = (\text{potential height growth}) \times (\text{height competition})$$

or

$$G_H = P_H \times C_H$$

where P_H and C_H are the potential and competition factors for height growth.

For predicting tree height, the site index curves by **Biging and Wensel (1984b)** are used as a basis for the potential growth function P_H. The general process is to project a change in height along the site curve from the current height on the site curve to a height 5 years later. The current tree height is used to assign an hypothetical "age", A_1, to the tree. Then the height after a 5-year growth cycle is obtained from the site index curve at the "age" of A_1 plus 5 years. Thus, we express the current height of the tree (H_1) as a function (g) of A_1 and the site index (S):

$$H_1 = g\ (A_1, S)$$

Solving this expression for A_1, we get the inverse function g^{-1} yielding

$$\hat{A}_1 = g^{-1}\ (H_1, S)$$

and H_2, the estimated potential height at the end of the 5-year growth cycle, becomes

$$H_2 = g\ (\hat{A}_1 + 5, S)$$

The estimated potential height growth equation, P_H, then becomes

$$P_H = H_2 - H_1$$

This process of estimating the potential height growth is illustrated using the site index curve shown in **Figure 12.**

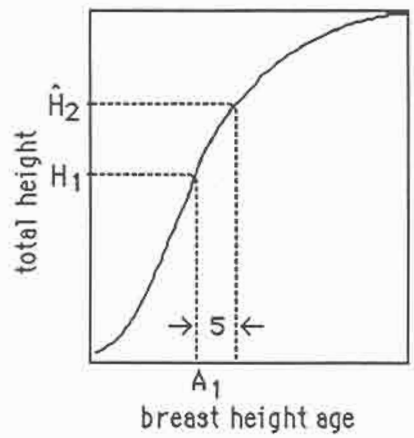

Figure 12. Height growth potential determination.

It should be noted, however, that the site index curves usually represent the height growth of an average dominant or codominant tree. Thus in applying the above process, the given site index was increased by 6 to 32 feet to allow prediction of potential height growth that was greater than the average. The table of adjustments added to the site index is given by **Wensel and Koehler (1985)**. These adjustments are used in the growth projection system.

The tree height growth competition factor, C_H, is obtained empirically for each species. The general process was to fit a non-linear function to the difference between the actual tree growth and the potential height growth obtained from C_H above. The competition is assumed to be related to the amount of tree crown canopy that is in competition with each subject tree. Also, for ponderosa pine, the competition relationships for that species appeared to change when it represented a large portion of the basal area. Thus, the percent basal area in ponderosa pine (PBA) was included in the prediction of competition for that species.

Both the crown closure at 66% of the tree's height (CC_{66}) presented in the previous section and the live crown ratio (LCR) were used in developing the competition factor for height growth competition. As competition increases, as indicated by larger values of crown closure (CC_{66}) the value of C_H decreases. Also, for given values of CC_{66}, C_H increases with live crown ratio (LCR).

In general terms, then, the height growth competition factor, C_H, is a function of CC_{66}, LCR, and PBA, where C_H is inversely proportional to the stand competition (expressed as a power of CC_{66}) and directly proportional to the capacity of a tree to respond (expressed as a power of the LCR).

The mathematical forms of the equations for P_H and C_H are given by **Wensel and Koehler (1985)**, along with tables of the coefficients for the equations.

Diameter growth

The process used for predicting diameter growth is similar to that used for height growth. Here the change in DBH^2, G_D, is predicted as a product of the potential and competition factors expressed as

$$G_D = (\text{potential } DBH^2 \text{ growth}) (\text{diameter competition})$$

or

$$G_D = P_D \times C_D$$

where the potential component, P_D, is similar in form to that of P_H depicted in **Figure 9**. However, since diameter growth is more sensitive to competition, curves analogous to site index are not possible to fit without the simultaneous fitting of the competition component, C_D.

As with height growth, the diameter competition increases as CC_{66} increases. However, trees with more crown had more diameter growth. Thus diameter growth competition is expressed as a function of both CC_{66} and CV, that is,

$$C_D = f\,(CC_{66}, CV)$$

where CV is the estimated crown volume of the tree.

The mathematical forms of the equations for P_D and C_D are given by **Wensel and Koehler (1985)**, along with tables of the coefficients for the equations.

Pseudo-stochastic effects

The variability inherent in the growth predictions is represented in the simulations by adding "pseudo-stochastic" effects. Rather than making a single growth prediction for each tree record, the trees-per-acre weight assigned to that tree is divided up and estimates are computed for each portion to give slower than average, average, and faster than average predictions. This is very much like allowing a confidence interval to represent a prediction rather than a single number.

The statistical distribution of errors in growth estimation for both diameter and height were represented by a skewed normal distribution as illustrated in **Figure 13**. The pseudo-stochastic

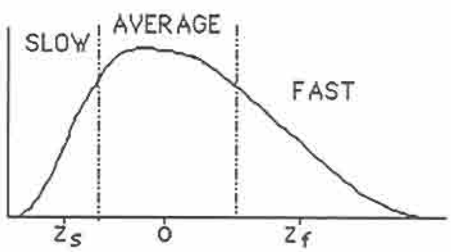

Figure 13. Skew-normal distribution used for pseudo-random effects.

effects were added to the estimates by computing Z scores for height and diameter. That is, with pseudo-stochastic effects, the growth predictions G' are computed as

$$G' = G\,(\,1 + z\,SE\,)$$

where $z = z_s, z_a, z_f$ for slow, average, or fast predictions, respectively, and SE is the standard error of the estimated growth rate. Note here that $z_a = 0$ produces $G' = G$ which is the growth of the initial tree record.

The following combinations of predictions were used, totalling 5 "pseudo-" records for each initial record.

Height Growth	Diameter Growth: slow	average	fast
slow		X	
average	X	X	X
fast		X	

The trees-per-acre weight of the initial tree record now must be divided over the 5 records. The standard errors, Z scores, and weights given to the 5 records are given by **Koehler and Wensel (1985)**.

THE CACTOS SYSTEM

The **CACTOS** system consists of the following three computer programs:

CACTOS	the CAlifornia Conifer Timber Output Simulator,
STAG	the **ST**And **G**enerator to generate stand descriptions for **CACTOS**, and
Entry	to facilitate the entry and editing of stand descriptions from the keyboard,

where the stand is description by a list of tree measurements, referred to as the tree list. These programs enable the user to create a tree list to represent a forest stand, to simulate the development of that stand through 5-year growth cycles (with or without partial harvests, mortality, or ingrowth), and to create yield summaries for use in management planning. A brief description of these programs is given here, however the user is referred to the publications cited for more detailed description sof the capabilities and operation of the programs.

CACTOS, the simulator

At the heart of **CACTOS** are the growth equations: diameter, height, crown recession, and mortality (**Wensel and Koehler, 1985**). **CACTOS** uses these equations to simulate the changes that take place in young-growth conifer stands in the mixed conifer region of northern California, by predicting the growth of individual tree records that represent the stand. The growth equations use the coop site index system developed from the stem analysis plots (**Biging and Wensel, 1984**). The crown models are used in this growth process to help estimate the competition affecting an individual tree (**Van Deusen and Biging, 1984**).

There are 4 distinct processes in **CACTOS**, each under the control of the user: reading a stand description, growth of the tree records, harvesting, and report generation. These processes, illustrated in **Figure 14**, are explained in more detail below.

Describing the stand to be simulated

CACTOS requires that the user enter a stand description to begin the simulation process. This stand description consists of the coop site index (**Biging and Wensel, 1984**) of each species present, and a tree list giving the species, DBH, total height, live crown ratio, and weight per acre for each tree being used to represent the stand. **CACTOS** stand descriptions can be easily prepared using the auxilary programs, **Entry** and/or **STAG** described below.

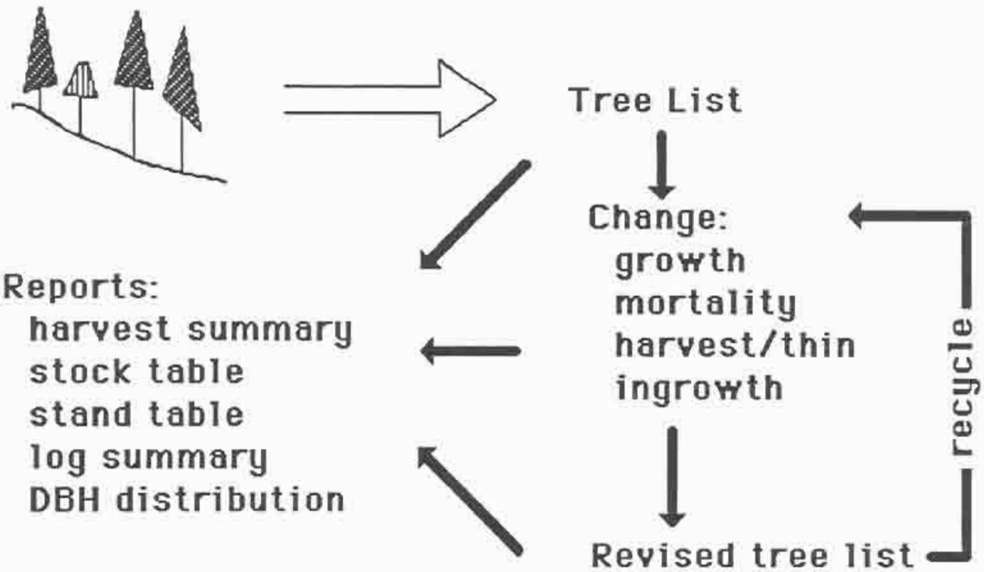

Figure 14. Flow of data through CACTOS

Entry is an interactive editor specifically designed to create stand descriptions for **CACTOS**. New stand description and ingrowth input files may be created, and old descriptions may be easily edited using Entry. Tree lists produced by **STAG** (below) can be edited interactively using **Entry**.

Tree growth simulation

CACTOS predicts the growth in DBH, total height, and height to the crown base in 5-year cycles. Thus, as shown in **Table 4**, a 20-year projection is accomplished by requesting that four 5-year cycles be simulated. The 5-year cycle was selected to correspond to the 5-year inventory cycle on the coop permanent plots.

Currently ingrowth information is entered into the process by the user and not predicted by the computer. Thus if a projection is long enough for ingrowth to be a factor, the user would use the **Entry** program to create a list of ingrowth trees to be added to the stand description. This new stand description can be summarized and grown for additional 5-year cycles.

Table 4. Yield Summary for 20-year projection

YIELD SUMMARY: units = english

----

stand label = Demo Data Plot

	min. DBH	merch top
cubic ft.	0.0	4
board ft.	8.0	6

species	site	init. age
Pond. Pine	100.	30.
Cedar misc	80.	30.
Douglas Fir	90.	30.
White Fir	90.	0.

__Symbols and abreviations__

et	elapsed time (years)
dbar	average diameter (inches)
tpa	trees per acre (no.)
basar	basal area (sq.ar./acre)
cvol	cubic volume (M cu.ft./acre)
bdvol	board volume (M bd.ft./acre)
bagro	5-year basal area growth (sg.ft./acre)
cvgro	5-year cubic volume growth (Mcu.ft./acre)
bdgro	5-year board volume growth (M bd.ft./acre)

species	et	dbar	tpa	basar	cvol	bdvol	bagro	cvgro	bdgro
Pond. Pine	0.	22.42	25.0	68.5	2.38	13.85	0.	0.	0.
Cedar misc	0.	13.61	45.0	45.5	.86	3.61	0.	0.	0.
DouglasFir	0.	18.11	50.0	89.4	2.89	15.77	0.	0.	0.
White Fir	0.	6.79	100.0	25.2	.42	1.09	0.	0.	0.
Totals	0.	13.80	220.0	228.6	6.55	34.33	0.	0.	0.
Pond. Pine	5.	23.33	24.7	73.2	2.68	16.07	4.7	.30	2.22
Cedar misc	5.	14.33	43.4	48.6	.96	4.30	3.1	.11	.69
DouglasFir	5.	19.03	48.7	96.2	3.29	18.44	6.8	.40	2.67
White Fir	5.	7.96	79.6	27.5	.53	1.65	2.3	.11	.56
Totals	5.	15.14	196.4	245.5	7.46	40.47	17.0	.91	6.14
Pond. Pine	10.	24.22	24.3	77.9	2.99	18.43	4.7	.31	2.35
Cedar misc	10.	15.02	42.0	51.7	1.07	5.03	3.0	.11	.73
DouglasFir	10.	19.93	47.6	103.1	3.70	21.28	6.9	.41	2.84
White Fir	10.	8.79	70.7	29.8	.64	2.37	2.3	.11	.72
Totals	10.	16.14	184.6	262.4	8.39	47.11	16.8	.94	6.64
Pond. Pine	15.	25.08	24.1	82.6	3.31	20.90	4.7	.32	2.47
Cedar misc	15.	15.69	40.7	54.6	1.18	5.71	3.0	.11	.68
DouglasFir	15.	20.82	46.5	110.0	4.12	24.28	6.9	.42	3.00
White Fir	15.	9.49	65.0	31.9	.75	2.95	2.2	.12	.58
Totals	15.	17.04	176.3	279.1	9.36	53.84	16.7	.96	6.73
Pond. Pine	20.	25.92	23.8	87.2	3.63	23.48	4.7	.32	2.58
Cedar misc	20.	16.34	39.5	57.5	1.28	6.41	2.9	.11	.70
DouglasFir	20.	21.68	45.6	117.0	4.55	27.41	7.0	.43	3.13
White Fir	20.	10.12	60.9	34.0	.87	3.57	2.1	.12	.63
Totals	20.	17.87	169.7	295.7	10.34	60.88	16.6	.98	7.04

Timber harvesting

In addition to simulating growth in five year cycles, **CACTOS** allows the user to harvest the stand. The program offers four harvesting routines, and allows considerable flexibility in simulating harvest. The harvest routines consist of a harvest with DBH control, a harvest with basal area control, a sanitation harvest, and a free harvest. All harvest routines allow the user to specify the species to be cut.

Report generation

CACTOS automatically provides a yield summary by 5-year periods for the total simulation. An example of the yield summary is given in **Table 4.** In addition, **CACTOS** creates a report file which stores the portions of the screen output that are selected by the user during the simulation. These optional reports include: a listing of the tree records, the diameter distribution of the stand, a diameter class table, and a standing/harvest log table. The volumes reported and the number of logs are calculated using the Coop tree volume and stem taper equations discussed earlier.

CACTOS allows the user to specify the minimum DBH and the minimum merchantable top diameter to be used in reporting stand volume and volume growth. The user may also specify how species or species groups are to be handled in reporting stand statistics, and how much detail is to be reported (ranging from the growth detail of individual tree records to only a summary of the total stand growth). **CACTOS** has a standard set of these specifications which simplify the program's use.

The program code

The basic structure of **CACTOS** and much of the actual program code are derived from CRYPTOS, the Cooperative Redwood Yield Project Timber Output Simulator (**Krumland and Wensel, 1982**). **CACTOS** is written in ANSI standard FORTRAN, commonly known as FORTRAN 77. The program code has been constrained to conform to an enhanced version of "Subset FORTRAN" to allow **CACTOS** to run on an IBM PC-compatible personal computer. Both the mainframe and the PC version have the same capabilities and, with the optional math coprocessor chip installed, execute at about the same speed. The programs in the **CACTOS** system are copyrighted by the University and executable copies for IBM PC-compatible computers can be obtained from the authors.

STAG, the stand generator

Since the user may want to do simulations using stand descriptions for which not all of the required information is available for each tree, tree heights or heights to the crown base can be generated by the program **STAG**, the **STA**nd Generator (**Van Deusen and Biging, 1984**).

In terms of the data available to describe forest stands to be simulated using **CACTOS**, typical scenarios are as follows: (1) only tree DBH is measured on all trees with a subsample of the trees measured for tree height and height to the crown base; (2) heights to a merchantable top are measured instead of total height; (3) only numbers of trees by species and DBH class are provided; and (4) only basal area and number of trees by species are provided. Since these scenarios are common, **STAG** was developed to use such incomplete data to generate complete tree lists that are required by **CACTOS**. Thus, **STAG** represents an interface between the forest manager and **CACTOS**.

Technical details and examples of the processes used in **STAG** are included in the **STAG** User's Manual, Research Note No. 11 (**Van Deusen and Biging, 1985**) and in the PhD dissertation by **Van Deusen (1984)**. The user's manual also provides useful examples and discusses optimal uses for the features of the program.

CURRENT STATUS

CACTOS, and its supporting programs **STAG** and **Entry**, make up the **CACTOS** system. Although there are many facets of our cooperative growth and yield research program, these computer programs have been the focus of our research because they contain the individual results from all aspects of our research program. The mathematical representations of volume and taper, site index, crown profile, basal area and height growth relationships described separately are all incorporated in this system. These representations will continue to be tested by us and by our cooperators and, as needed, revisions of the models will be made.

A preliminary version (1.0) of the **CACTOS** system was released to the cooperators in the fall of 1984 for testing. The cooperators had an opportunity to run the simulators in the released version (1.0) as well as earlier test versions. Their comments have been helpful in preparing version (2.0) now released. While the **CACTOS** system will continue to evolve, it will continue to represent both a summary of our research and its final product.

This cooperative research project has produced much more than the simulation programs. Other benefits of the work include the following:

Continuing forestry education

Participation of practicing foresters in this research has served to educate both these foresters and the University staff. The industry and University cooperators shared experiences, concepts, theories, and practices with each other during their periodic office and field meetings. This provided a forum for instruction, discussion, and self help.

Compatible data structures

Field plot and measurement definitions have been standardized for the stem analysis and permanent plot data bases. While some differences still exist due to past practices, this standardization makes it possible to pool data from a variety of sources to develop prediction models that can be used by all of the cooperators. This pooling of data has the potential of developing more broadly based and more robust mathematical models than could be obtained using data from any one company. Thus valid models can be developed to enable a forest manager to make growth predictions for stand conditions for which they did not collect data.

Installation of long-term growth plot data structures

Mortality rates, the amount of lag time after thinning, as well as diameter and height growth rates are best estimated from plots monitored over a longer time frame than the current study. The initial coop measurement of the permanent plots was the only measurement up to coop standards. However, in many cases the coop plot locations coincide with permanent plots that have had previous measurements. In these previous measurements tree diameter (DBH) was the principal variable measured with tree merchantable heights recorded for some trees.

Tree total height was occasionally measured. More than half of the coop plots have been remeasured in 1984 with the balance of the remeasurements expected in 1985 -- except for plots lost due to changes in ownership.

The permanent plots established as part of this study will continue to be monitored with the expectation of the first complete remeasurement being analyzed in 1986.

Improved mensurational practices

Through meetings and the establishment of measurement standards, measurement practices were improved. Where they occurred, these improved practices should make the data more useful for assessing change as compared to simply assessing current stocking levels.

Undergraduate and graduate education

The many students who have worked on various aspects of this project benefitted from the income of their part-time employments as well as from their experiences gained by the actual work. In meeting with cooperators in the field and at meetings, they were also given the opportunity to see some of the problems faced by forest managers, making their classroom educations more valuable. Some of the students were hired by the cooperators for summer work and at least one student now has a permanent job with a cooperator. Thus this project has enhanced the students' educations and has provided some of the cooperators with excellent employees.

Cooperation for future projects

In addition to the topics studied by the current project, the seeds of cooperation have been planted for research in stand management, decision making, soil and nutrient management, forest inventory, as well as continued research in growth and yield. Also, the University researchers are more sensitive to the problems of the forest managers and better able to make decisions on the direction of their research to provide greater benefits to the managers.

FUTURE WORK

The models in the **CACTOS** system will continue to evolve. As our knowledge of forest stand development increases, this knowledge will be incorporated into the computer programs of the **CACTOS** system. Development will take place along four principal lines: (1) the development of improved diameter growth predictors using permanent plot data, (2) testing and calibration, (3) corrections and expansion of capabilities of the **CACTOS** system, and (4) use of the system to study the impact of alternative management systems.

Improved diameter growth estimates

Improved growth equations are being developed from the previous measurement of the permanent plots. This work, which is underway, will utilize the diameter increment core data obtained by the cooperators at the time of the initial coop measurement. Early indications are that these data will enable us to obtain better estimates of diameter growth for the smaller trees than what is currently in the **CACTOS** model.

Testing and calibration

A formal program of testing and validation must be worked out to determine the conditions under which the predictions are valid. Even where the system is generally valid, calibration may be needed to improve the accuracy of the predictions. This testing and calibration will be done individually by the users as well as by cooperative efforts with the Berkeley staff. Should validation tests suggest that changes are needed in the programs, these changes will be made and distributed to all cooperators.

Corrections and expansions

The use of the **CACTOS** system will give rise to a demand for changes and expansion of the programs in both substantive and non-substantive ways. Non-substantive changes to the programs may be desired to improve the usefulness of the system or to make it easier to operate. These include changes in the output format or changes in the interactive structure of the programs.

Substantive changes in the programs are those that require additional research to define the mathematical relationships used in the simulations. The most pressing of these substantive changes are improvements in the mortality and ingrowth predictions, topics that have the highest priority for future research. The improvement in the measures of productive capacity of the site are anticipated as a result of work under way in cooperation with Professor Paul Zinke. When this research is completed changes in the programs may be needed.

Permanent plot remeasurement data will be obtained from the cooperators in the last half of 1985. After editing and correction, these data will be used for another round of modelling to both test the current models and, where the current models are found to be weak, to produce improved growth estimation equations for inclusion in a future release of **CACTOS**.

Use of **CACTOS**

Plans are underway to develop a "primer" to assist the users in planning experiments using the **CACTOS** system. This primer, which will supplement the user's manuals, will include strategies to be followed and examples. In addition, proposals are being developed by other Berkeley faculty (1) to study stand dynamics using the **CACTOS** system and, (2) to develop economic decision rules for maximizing management objectives (e.g., maximum value production). Also, short courses taught through the University's Cooperative Extension are providing instruction in the use of the **CACTOS** system in management planning.

IN CONCLUSION

The mind expansion that occurs when one starts to simulate the growth and yield of forest stands under alternative levels of stocking and thinning alternatives is exciting. Thus the very use of the **CACTOS** system will give rise to a demand for changes and expansion of the programs and for additional research. Further, this cooperative relationship within the University and forest industry will provide the framework for continued research in forest growth and yield as well as for cooperative research in other areas.

The authors encourage users of the **CACTOS** system to send reports on the extent of their use of the system, as well as comments on the features they like or dislike. The authors would like to receive comments on the accuracy of the predictions where comparisons can be made with growth measurements.

Literature Cited

Biging, Greg S. 1980.
Expanded stem analysis procedures. Northern Calif. Forest Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. 45 pgs.

Biging, Greg S. 1981.
Draft volume tables for young-growth mixed conifers of northern California. Part I: Volume tables for mixed conifers Part II: Taper equations for mixed conifers. **Research Note #2.** Northern Calif. Forest Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. 56 pgs.

Biging, Greg S. 1983.
Volume tables for young-growth mixed conifers of Northern California based upon the stem analysis data. Part I: Volume tables for mixed conifers. Part II: Taper equations for mixed conifers. (Revised draft). **Research Note #7.** Northern Calif. Forest Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. 59 pgs.

Biging, Greg S. 1984a.
Taper equations for second-growth mixed conifers of Northern California. **Forest Science** 30(4):1103-1117.

Biging, Greg S. 1984b.
Improved estimates of site index using a varying-parameter model. **Forest Science** 31(1):248-259.

Biging, Greg S. and Lee C. Wensel. 1984a.
A photographic technique for use with stem analysis. **Forest Science** 30(3): 715-729.

Biging, Greg S. and Lee C. Wensel. 1984b.
Site index equations for young-growth mixed conifers of Northern California. **Research Note #8.** Northern Calif. Forest Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley.

Dunning, Duncan and L. H. Reineke. 1933.
Preliminary yield tables for second growth stands in the California pine region. USDA Tech. Bulletin No. 354. 23 pgs.

Pienaar, L.V. and K. J. Turnbull. 1972.
The Chapman-Richards generalization of Von Bertalanffy's growth model for basal area growth and yield in even-aged stands. **Forest Science** 19:2-22.

Koehler, James R. and Lee C. Wensel. 1985.
Psuedo-stochastic effects. **Research Note #14.** Northern Calif. Forest Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. __ pgs.

Krumland, Bruce E. and Lee C. Wensel. 1982.
CRYPTOS / CRYPT2 user's giude. Cooperative **R**edwood **Y**ield **P**roject **T**imber **O**utput **S**imulator. Version 4.0. Research Note No. 20, Cooperative Redwood Yield Research Project. Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. 27 pgs.

Robinson, Barry N., Anderson, Gary D., Cohen, Eli, Gazdzik, Wall F., Karpel, Lenny C., Miller, Alan H., and Stein, Jack R. 1980.
SIR. Scientific Information Retrieval. User's Manual. Version 2. SIR Inc. Evanston, Ill.

Van Deusen, Paul C. and Greg S. Biging. 1985.
STAG. A **STA**nd **G**enerator for mixed species stands. Version 2.0 **Research Note #11.** Northern Calif. Forest

Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. 25 pgs.

Wensel, Lee C. and Peter J. Daugherty. 1985.
CACTOS user's guide: the **CA**lifornia **C**onifer **T**imber **O**utput **S**imulator. **Research Note #10.** Northern Calif. Forest Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. 98 pgs.

Wensel, Lee C. and James R. Koehler. 1985.
A tree growth projection system for Northern California coniferous forests. **Research Note #12** Northern Calif. Forest Yield Cooperative, Dept. of Forestry and Resource Mgmt., Univ. of Calif., Berkeley. 9 pgs.

APPENDIX A

Table A1. Summary of symbols for variables and relationships used in analyses.

A	breast height age
A_1	hypothetical tree breast height "age"
C, C_H, C_D	competition function: general, height, and DBH-squared
CA(h)	tree crown cross sectional area at height h
CC_{66}	stand crown closure at 66% of tree height
CV	tree crown volume
D or DBH	diameter at breast height
f	"is a function of"
g(A)	site index function giving height of tree at breast height age A
$g^{-1}(H)$	inverse function giving "age" for tree of height H
G, G_H, G_D	5-year growth: general, height, and DBH-squared
G'	growth prediction with pseudo-stochastic effects
h	height ($0 \leq h \leq H$)
H	total height
H_1	initial tree total height
H_2	estimated potential tree total height at end of 5-year period
HCB	height to the crown base
LCR	live crown ratio ($1 - {}^{HCB}/_{H}$)
P, P_H, P_D	potential growth: general, height, and DBH-squared
PBA	percent basal area (of a species)
S	site index, 50-year breast height age
SE	standard error
sp	species
TPA	trees per acre
z, z_s, z_a, z_f	standardized (skewed) normal deviations: general, slow, average, and fast growing trees