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Biometric Models and Simulation Techniques for Processes of Research and Applications in Forestry

Biometrische Modelle und Simulationstechniken bei Prozessen in forstlicher Forschung und Praxis

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YIELD FORECASTING SYSTEMS: WHAT'S AVAILABLE

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SUMMARY

A variety of Douglas-fir yield forecasting systems are currently available to assist decision-makers. This paper describes some of these systems and reviews their availability and application in the Pacific Northwest. These systems provide satisfactory estimates for natural stands, with or without commercial thinning. They are much less satisfactory for intensively managed plantations or natural stands with early spacing control. Development of these systems has been hampered by the absence of long-term growth records covering a wide range of site classes, ages, and management practices.

INTRODUCTION

For most of this century, yield tables have been extensively used by forest managers to depict the development of stands over time. Typically key stand parameters such as basal area, diameter, number of trees and net volume are shown for successive stand ages. These yield tables have formed the basis for many subsequent decisions involving the timber resource. Some uses of yield tables as cited by Hamilton and Christie (1973) are:

(a) production forecasting,
(b) evaluation of alternative treatments,
(c) valuation and
(d) yield control.

Production forecasting utilizes yield table estimates when making calculations of:

(a) long-term sustainable harvest levels, timber harvest schedules and land management plans, and
(b) short-term inventory projections.

While it is reasonable to assume future growth and yield similar to past growth when making short-term forecasts, long-term projections require estimates of the future consequences of management practices undertaken today. Thus, differing types of yield forecasting systems may be needed to satisfy both needs.

Yield estimates are also necessary for conducting economic appraisals of alternative stand treatments such as thinning, fertilization, pruning or the determination of the optimal financial rotation age. Yield estimates also form the basis of valuation studies which are undertaken for tax assessment, damage appraisal or sale preparation purposes. Lastly, yield tables are used to control the development of the growing stock in individual stands. In essence, no matter what the ultimate use, a yield table provides a convenient estimate of the yield of timber products, of certain sizes and qualities, that can be expected from a specific land area managed under a particular management regime.

While the uses of yield tables have remained fairly constant over the past century, there have been dramatic changes in the <u>type</u> of yield tables and the <u>means</u> used to produce them. Three <u>types</u> of yield tables have been introduced into American forest management during the past century:

(a) normal,
(b) empirical or variable density, and
(c) managed stand.

Each of these yield table types was introduced to respond to managerial needs of the time. However, as these needs and the character of the resource changed, the relative importance of each type of yield table also changed. Further, the <u>means</u> used to develop yield tables have also changed over time, evolving from free-hand curves to alignment charts (for plotting anamorphic curves) to statistical curve fitting (involving first linear and later non-linear regression models) to calculus-based compatible growth and yield models to computer simulation forest growth models (Tesch, 1981; Ek and Monserud, 1981). Today, owing to the diverse nature of the timber resource, all of these yield table types are used within the Douglas-fir region in North America.

The purpose of this paper is to describe some of the coastal Douglas-fir yield forecasting systems which are available to, and used by, forest managers. Two primary sources are the basis of the review:

(a) a search of the published literature and
(b) a 1985 survey of organizations and individuals in the Douglas-fir region who have developed or use yield forecasting systems.

This review covers the range of data used to develop each system, the type of stand treatments included and the accessibility of the system. Other existing surveys showing the status of growth and yield information in the Pacific Northwest are those of Hann and Riitters (1982), Knapp, Curtis and Cochran (1984) and Reimer and Lussier (1984). Many of the Douglas-fir yield forecasting systems briefly described below are discussed in more detail in these literature surveys. Further, a large number of overview articles have been published in the past 10-15 years. While not specific to coastal Douglas-fir, these articles provide substantial background information concerning the evaluation of growth and yield modeling. A few of the more noteworthy surveys are those of Curtis (1972), Moser (1980), Munro (1984), and Titus and Morton (1985).

DOUGLAS-FIR YIELD FORECASTING SYSTEMS

Normal Yield Tables

The earliest form of yield table used in North America in the Douglas-fir region was the normal yield table. These tables show expected stand yields for natural fully-stocked (i.e., normal) stands in an undisturbed state where no management interventions are anticipated. The tables usually show net yield as a function of stand age and site index (100-yr. base). The most comprehensive normal yield table used in the Douglas-fir region is that of McArdle, et al. (1961). Originally published in 1930, the tables were slightly revised in 1949 and again in 1961. Data used in the development of the yield tables came from 1,916 plots in 245 tracts located throughout western Oregon and Washington. Data ranged in age from 20-180 years across a site index range of 80-200 ft. The tables provide yields for a variety of diameter limits, volumetric units, and top diameters. They also provide estimates of number of trees, average diameter, basal area and height. Staebler (1955) and Curtis (1967) extended these tables by providing estimates of gross yields. Nelson and Bennett (1965) summarize the well known pros and cons of using normal yield tables. However, despite their limitations, they are still used today, although they are becoming of limited value as more plantation acreage accumulates.

Empirical/Variable Density Yield Tables

Empirical or variable density yield tables provide an estimate of net yield as a function of stand age, site quality and some measure of stand density. Only natural, unmanaged stands with no subsequent management interventions are modeled following this approach. Clearly, however, yield forecasts utilizing density as an additional independent variable are an improvement over the earlier normal yield table approach. McKeever (1947) developed a set of empirical yield tables which modified the McArdle and Meyer (1930) normal yield tables by introducing three stocking classes. He also applied the Briegleb-Girard (1943) growth correction factors to account for changes in density as understocked stands approach normality over time. Only net yield tables showing Scribner board foot volumes for live trees $\geq$ 11.6 inches in diameter to an 8-inch top diameter were provided, thus limiting the usefulness of the tables.

Chambers (1980) developed a set of variable density yield tables for western Washington Douglas-fir using stepwise multiple linear regression. Independent variables utilized were breast height age, site index (50-yr. base) and percent normal basal area. The tables were based on 356 permanent and 30 temporary plots. Ages ranged from 9-130 years, and site index ranged from 38-165 ft. (50-yr. base). A variety of tables depicting basal area, number of trees, average tarif, quadratic mean diameter, cubic and Scribner board foot volumes and average height are provided. A BASIC Computer program was written to generate the yield tables and is available from Chambers (1980). Tests of these yield tables have been very favorable. Chambers (1976) compared the reliability of an earlier version of his empirical yield tables against actual cruise information for five areas in western Washington and Oregon and one area on the east slope of the Cascades. He found that the percent difference between the cruise estimates and the yield table estimates differed by -1.5 to +5.0 % for total stem cubic volume and -2.5 to +8.5 % for Scribner board foot volume to a 6-inch top diameter. The average percent difference over the tests was +1.0 % and +1.5 % for the two volumetric measures, respectively.

Fligg (1960) developed a set of empirical yield tables for coastal Douglas-fir based on over 13,000 inventory clusters (4 or more plots) scattered throughout British Columbia. Yield tables were provided for different forest inventory zones. Only cubic foot volume to a 4-inch top diameter for differing diameter limits was provided. Recently, the British Columbia Ministry of Forest completed the development of a variable denstiy yield projection system for use throughout British Columbia (Viszlai, 1982, 1983). These tables utilize a modified Chapman-Richards non-linear yield model to estimate stand volume, diameter and basal area as a function of site index (50-yr. base), crown closure, basal area and diameter. These tables replace an earlier series of hand drawn volume/age curves used in British Columbia prior to 1978. A total of 1501 sample of pure (at least 81 percent Douglas-fir by volume) coastal Douglas-fir were used in the development of the equations. This involved a combination of temporary inventory samples, permanent growth samples and permanent productivity samples. Total ages ranged from 15-135 years; site index (50-yr. base) from 14-45 m.; and crown closure from 5-95 percent. The yield tables include estimates of diameter, basal area, number of stems and net volume in cubic meters for three diameter limits and differing utilization standards. As with all coastal Douglas-fir variable density yield tables, the system is only applicable to unmanaged, natural stands. This stand-based system has been programmed for a variety of computers and is available in both batch and interactive versions from the B.C. Ministry of Forests.

Managed Stand Yield Tables

Most of the recent effort in developing new yield forecasting systems for coastal Douglas-fir has been directed at the development of computer-based forest growth models. These differ from normal and variable density yield tables in several important respects. First, these models produce yield estimates by accumulating annual or periodic annual increments over time. Functions for directly estimating yield are not part of these models. Second, these growth models are capable of simulating the consequences of a variety of management treatments.

Lastly, these models provide estimates of gross yields as well as net yields over time. Munro (1984) and Hann (1978) have classified these models into two types:

(a) stand models and
(b) individual tree models.

Stand models are further stratified into:

(a) diameter free
(b) diameter distribution and
(c) diameter class models.

Mitchell (1980) and Mitchell and Cameron (1985) have further extended this classification by recognizing crown/bole models which operate at the sub-tree level. Since these latter models retain inter-tree distances, they are an extension of the distance dependent individual tree models. The pros and cons of these various model types are discussed by Munro (1974, 1984), Knapp et al. (1984), Bare et al., (1984), Mitchell and Cameron (1985) and Ek and Monserud (1981).

Several well known whole stand diameter free models exist for coastal Douglas-fir. In chronological order of development these are:

(a) Hoyer (1975)
(b) DFIT (Bruce at al., 1977 and Reukema and Bruce, 1977)
(c) DFSIM (Curtis et al., 1981, 1982).

Hoyer's model was developed from 308 plots taken in western Oregon and Washington covering site indices of 60-140 ft. (50-yr. base) and ages of 11-42 years. Sixty-seven of the plots were thinned and 241 were unthinned. This whole stand diameter free simulator estimates average height, number of trees, quadratic mean diameter, average tarif, cubic volume and Scribner board foot volume before and after thinning. In addition to thinning, the model is capable of estimating the future yields caused by the addition of nitrogen fertilizer. The model was written in Fortran and is available from Hoyer (1975).

The DFIT (Douglas-fir Interim Tables) model depicts the development of pure stands of coastal Douglas-fir under various forms of intensive management including commercial and pre-commercial thinning and fertilization. The whole stand diameter free model is based on a combination of data from McArdle et al., (1961) plus more recent work (Reukema 1975 and Reukema and Bruce 1977).

The basic components of DFIT are:

(a) equations describing the development of natural stands,
(b) thinning guides based on Reineke's stand density index,
(c) equations describing the total cubic-foot increment of thinned stands and plantations,
(d) equations predicting amount and timing of mortality in natural stands,
(e) a method for describing stand components at intervals without the direct use of stand and stock tables, and
(f) many assumptions about mangement practices and their effects on stand development

(Bruce et al., 1977). The yield tables produced by this model depict stands in terms of quadratic mean diameter, basal area, height, total and merchantable cubic volume and Scribner and International board foot volume for both harvested and residual trees. The model is written in Fortran and is available on several types of computers. Brodie and Kao (1979) developed a dynamic programming model (DOPT) which finds an optimal management prescription given the available DFIT options. While DFIT continues to be used, it was superseded in 1981 with the development of the DFSIM model.

DFSIM (Curtis et al., 1981, 1982) was the result of a combined U.S.D.A. Forest Service and Weyerhaeuser Company effort to pool their data with that of other organizations in the Douglas-fir region to develop a managed stand yield table for coastal Douglas-fir. DFSIM differs from DFIT in that a more complete data base was used in its development; it is based on empirically-derived, and not theoretical, relationships; and it represents a wider range of stand conditions and management options (Curtis et al., 1981). This whole stand diameter free model incorporates precommercial and commercial thinning and nitrogen fertilization activities. Approximately 203 installations consisting of 1,434 plots were used to develop the model. Total stand age ranged from 10-90 yrs; site index from 52-162 ft. (50 yr. base); and covered a wide range of densities (although most plots were in fairly dense stands). Of the 1,434 plots available as of 1974, 1,076 were in natural stands and 358 were in plantations. Little data were available for plantations older than about 40 years; for any stand over 80 years; for stands with repeated fertilizations; for wide initial spacings (i.e., less than 300 established trees per acre); or for stands fertilized with more than 400 lbs. of nitrogen per acre.

The principal functions incorporated in the model for juvenile stands (quadratic mean diameter $<$ 5.55 inches) are:

(a) top height,
(b) top height increment,
(c) number of stems per acre,
(d) quadratic mean diameter and,
(e) mortality.

For stands with a quadratic mean diameter $\geq$ 5.55 inches, the principal functions are:

(a) top height,
(b) gross and net increments in basal area and volume,
(c) net increment in quadratic mean diameter, and
(d) mortality.

DFSIM produces estimates of a wide variety of stand parameters, including quadratic mean diameter, basal area, top height, number of trees, cubic volume, and International and Scribner board foot volumes. A large variety of thinning schedules, stand types and juvenile stand options can be evaluated using DFSIM. The model is coded in Fortran and is available in both batch and interactive formats for a variety of computers.

Two off-shoots of DFSIM are DP-DFSIM, a dynamic programming model similar to DOPT (Johnson and Sleavin, 1984), and DFSIM with Economics (Fight et al., 1984). This latter model allows the user to estimate the present net worth of any simulated management prescription generated by DFSIM. An interactive program is available to help the user generate the input file required by DFSIM with Economics.

While lesser known than the above models, Rustagi and Diaz (1976) developed TIMBER as a whole stand diameter free model. This model grows pure stands of Douglas-fir in the presence of thinning and fertilization. This empirical model is driven by dominant height, basal area and number of trees per acre. Both clearcutting and shelterwood are available as options for final harvest. Available regeneration methods include natural, seeding and planting. Model outputs show average diameter, top height, basal area, number of trees, total cubic volume and a cash flow summary. The model is written in Fortran and is available from Professor Rustagi.

While no whole stand diameter distribution and/or diameter class models exist (in the public domain) for coastal Douglas-fir, several individual tree models do exist. Newnham (1964), Lin (1974), Arney (1974) and Mitchell (1975, 1980) have developed individual tree distance dependent forest growth models. Only Mitchell's TASS (Tree and Stand Simulator) model will be discussed in any detail. As described by Mitchell and Cameron (1985), "This crown-based model grows trees in a simulated three dimensional growing space. The crowns of individual trees expand and contract asymmetrically in response to internal growth processes, physical restrictions imposed by the crowns of competitors, environmental factors (site quality, defoliation, and animal damage), and cultural practices (thinning, pruning, and fertilization).

The crowns add a shell of foliage each year that benefits the tree in diminishing amounts for several years. The volume increment produced by the foliage is distributed over the bole annually and accumulated to provide tree and stand statistics". The system has recently been used to develop a new set of managed stand yield tables for coastal Douglas-fir (Mitchell and Cameron, 1985). Management activities included in the model are commercial thinning, fertilization, pruning, browsing damage, and defoliation. The major processes which are incorporated into TASS are:

(a) height growth,
(b) branch extension,
(c) accumulation of foliage,
(d) production and distribution of bole increment,
(e) suppression of height growth, and
(f) mortality.

Site quality, inter-tree distance and the above listed management activities affect these processes. Other than initial spacing, little work has been undertaken to calibrate and validate yield responses. The only feature that identifies unmanaged stands is the spatial distribution (e.g. random, clumped) of trees at establishment. All coefficients are the same for both managed and unmanaged stands.

Data used to develop TASS came from trees 20-60 years of age growing on medium to high site indices. A wide representation of crown classes were used to develop the model. As with all distance dependent models, the user must either provide tree coordinates or the spatial distribution which characterizes the stand. In addition, TASS requires plot dimensions, number of trees, site index and type, and intensity of management treatments. Although programmed in Fortran IV, the TASS model is not commercially available. Those interested in using the model should contact Dr. Kenneth Mitchell at the B.C. Ministry of Forests, Victoria, Canada.

A readily available individual tree distance independent forest growth model is the Stand Projection System (SPS) developed by Arney (1985). SPS is the only model of its type that is generally available for coastal Douglas-fir forests. The model, based on a portion of the same data base used to develop DFSIM, utilized 492 plots (46, 670 trees) from natural stands and 153 plots (13, 181 trees) from plantations. The trees used in the development of the model ranged in age from 13 to 72 yrs., although no plantation-grown trees were over 40 years of age, and site index (50-yr. base) ranged from 18-48 m. SPS is applicable to natural and managed stands and incorporates precommercial and commercial thinning, fertilization and initial spacing. No provisions are included for the effects of genetics, site preparation, seedling vigor, brush control or catastrophic mortality. SPS adopts the "potential/modifier" function approach described in STEMS (Belcher et al., 1982) and consists of five components:

(a) top height increment,
(b) tree diameter increment relative to a fixed top increment,
(c) tree height increment relative to a fixed top increment,
(d) tree mortality, and
(e) tree volume or taper equation.

Unlike STEMS and Prognosis (Wykoff et al., 1982) which use fixed time periods as growth steps, SPS uses a variable time period defined as the number of years required to produce 4.5 m of height growth. This interval increases with decreasing site index and initial tree height and leads to faster execution times than the fixed time increment models.

SPS is programmed in Fortran and is available for a wide variety of computers. Like other distance independent models, SPS can be used to project stand tables from inventory files or new cruises.

Proprietary Yield Models

All of the yield forecasting models discussed above, with the exception of SPS, reside in the public sector and are generally available for use by any interested party. However, there are a variety of other coastal Douglas-fir yield systems that have been developed by various forest products companies or consultants which are proprietary in nature. A partial review of these systems is included to provide some insight into the current state-of-the-art of yield forecasting in the private sector.

In 1982, the Weyerhaeuser Company completed development of SEER (System for Economic Evaluation of Regimen). A part of this model includes a managed stand yield forecasting system for coastal Douglas-fir. This whole stand diameter distribution model includes initial spacing, thinning, nitrogen fertilization and first generation genetic improvement as possible management activities. Yield estimates for unmanaged stands can also be obtained from the system. As with other yield forecasting systems, the data base for plantations, or early spaced natural stands, is very weak. The system is programmed in Fortran, but is unavailable outside of the company.

Crown-Zellerbach and Crown Forest Industries Limited use a whole stand diameter free model known as FRAME (Forest Resource Asset Management Evaluation). Completed in the late 1970's, the model is used for unmanaged as well as managed stands. Management activities included in the model are thinning and nitrogen fertilization. Data used to develop the model came from operational cruise plots, general inventory plots, research plots and the published literature. The model is programmed in Fortran but is not available outside of the company.

Boise Cascade Corporation has developed its own individual tree distance independent model for coastal Douglas-fir. They have also reviewed DFSIM and DFIT for possible use. Simpson Timber Company uses DFSIM, DFIT and SPS, but has not developed any Douglas-fir yield models of their own. Georgia-Pacific Corporation is using a modified version of the Prognosis model in western Oregon, but has no proprietary model of its own. Reimer (1980) described the McMillan Bloedel growth and yield program which consists of normal yield tables for second-growth natural stands and stocking and treatment guidelines for managed stands.

One additional model currently under development as part of the FIR project in Southwest Oregon is the individual tree distance independent model being developed by Dr. David Hann of Oregon State University. Scheduled for completion in 1986-87, this model can be applied to unmanaged and managed stands (thinning and possibly fertilization). The data base of 391 stands includes ages from 3-130 yrs. and site indices from 47-145 ft. (50-yr. base). Approximately 12, 700 diameter increments, 2,400 height increments and 450 crown measurements have been taken from 391 stands.

SUMMARY AND ASSESSMENT

In summary, this review of forecasting systems has provided some indication of the current state-of-the-art of growth and yield modeling in the Douglas-fir region of North America. The major conclusions of this review are:

1. We have good yield forecasting systems for natural, unmanaged coastal Douglas-fir stands, and for commercially thinned natural stands without early spacing control.

2. Due to a lack of long-term growth records covering a wide range of site classes and management practices, existing estimates for intensively managed plantations (especially those with low initial densities) and for stands with early density control are much less satisfactory.

3. As plantation forestry becomes more prominent, it it important that managed stand growth models be calibrated and reappraised against actual field performance. Current computer and modeling technology permits this type of feedback, but it is largely missing from existing models (Turnbull, 1978 and Stage, 1973).

4. We must continue to explore all possible modeling strategies that may lead to better yield estimates. Models such as FORCYTE (Forest Nutrient Cycling and Yield Trend Evaluator) a nutrient-based, process-oriented simulator (Kimmins, et al., 1983) and CLIMACS (Computer Linked Integrative Model for Assessing Community Structure) a forest succession model (Dale and Hemstrom, 1984), may be able to generate useful estimates of yield from basic ecological processes. Yield estimates produced by these structural models should complement those available from predictive models reviewed in this paper.

5. To facilitate future model development, it is imperative to continue efforts at standardizing and maintaining growth and yield data bases. A large amount of data currently exists and more will be forthcoming as efforts such as the Stand Management Cooperative began to take form.

6. Growth and yield modelers need to communicate closely with forest managers, economists, operations researchers and silviculturists to ensure that future models are designed to work efficiently with existing management information systems. Our models should also be tied much closer to product prediction models. We can no longer afford the luxury of building growth models without an end-user in mind.

ZUSAMMENFASSUNG

Augenblicklich können forstwirtschaftliche Planungen durch mehrere unterschiedliche Prognosemodelle für Douglasie unterstützt werden. Dieser Beitrag beschreibt einige dieser Modelle und diskutiert ihren Nutzen im Nordwesten der USA. Diese Modelle ermöglichen befriedigende Schätzungen für Naturwälder mit oder ohne Durchforstung. Sehr viel weniger befriedigend sind sie jedoch für intensiv gepflegte Pflanzungen oder Naturwälder mit früh einsetzender Standraumkontrolle. Die Entwicklung dieser Modelle wurde durch fehlende langfristige Wachstumsdaten behindert, die einen weiten Bereich von Standortstypen, Altersklassen und Bestandesbehandlungen abdecken.

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