STAND MODELLING FOR RADIATA PINE IN NEW ZEALAND

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ABSTRACT

Intensive forest management requires reliable information on stand dynamics, growth, and yield. A variety of modelling options will probably be required to provide information on which to base the full spectrum of forest management decisions. In this paper, modelling alternatives are regarded as part of a continuum of complementary systems rather than as mutually exclusive options. A brief overview of selected stand modelling alternatives is given, with some discussion of general situations for which the various approaches might prove efficient; and data bases for stand modelling are considered. Suggestions are offered for modelling Pinus radiata *stands in New Zealand.*

INTRODUCTION

Forest management decision-making requires stand-growth and dynamics information both for stands in current production and for stands that will exist in the future. The need for stand models varies with the intensity of management. As the intensity of management increases, the need for accurate growth and yield forecasts also increases. When species are grown for many different products and subjected to a wide variety of management regimes and treatments — as happens with *Pinus radiata* (radiata pine) in New Zealand — highly accurate and flexible systems for making growth and yield projections are essential.

The purpose of this paper is to discuss uses of stand models in forest management, and to provide a laconic overview of the full spectrum of modelling alternatives that have been applied to forest stands. Representative examples of the types of stand models discussed are cited to enable those involved in the construction of models to obtain more detailed information readily. However, this paper is not a comprehensive review of the forest stand-modelling literature: emphasis is placed on North American experience in stand modelling, and on work with radiata pine in New Zealand.

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Before proceeding further some important terms will be defined. Growth — generally synonymous with the term increment in forest mensuration — is the amount of increase in wood over a given period of time; yield is the total amount of wood available for harvest at any given time. Thus there exists a basic growth/yield relationship: yield is the summation of growth. Although most early stand-modelling studies were concerned with yield, and growth was obtained by differencing, many recent studies have emphasised growth rate or periodic increment, with yield estimated as the corresponding integral or summation. Throughout this paper, "stand models" is used as a general term to denote equations or systems of equations developed for providing information on forest growth and yield.

Forest stand-modelling is not a new endeavour for foresters. Early efforts involved "normal" yield tables constructed by graphical techniques. Modern quantitative tools were first employed as multiple linear regression analysis to predict forest yields. Continued advances in quantitative sciences and computing technology have now made possible highly sophisticated models of stand growth and dynamics.

USES OF STAND MODELS

Stand models are essential for decision-making under intensive forest management. Production forecasting, a traditional role of yield tables, continues to constitute an important use of stand models (Hamilton and Christie, 1974), and forecasts may be short or long term. Sometimes a total volume of the relevant portion of the stand may be sufficient for short-term forecasts, but more often information on volume by product-class and size-distribution within product-classes is needed. For long-term forecasts total volume often must suffice because future product-values and production costs are extremely difficult to project.

Stand models provide a means for evaluating treatment alternatives. Foresters must determine what species to regenerate, what initial spacing to use when planting, and how long the rotation should be. The feasibility of intermediate cultural treatments, such as thinning and fertiliser application, cannot be adequately evaluated without stand models which accurately reflect the effects of these treatments. Determination of impact of insect and pathogen attacks on forest growth and yield is required to evaluate the benefits of control measures.

Stand models are but one component in comprehensive systems of forest management; it is important to keep them in perspective and compatible with other components.

Management decisions are required for individual stands (necessitating highly detailed stand-data), for forests that are aggregates of many stands (in which case the detail needed about each stand is not likely to be great), and for broad regional or national planning situations (where detailed information on an individual stand basis is not needed).

Stand models can provide input information for decisions on matters ranging from local silviculture to national policy. With such diverse uses, and with the existing diversity of forest conditions, it is not surprising that a myriad of stand-modelling approaches has evolved.

MODELLING ALTERNATIVES

Forest-stand models may be divided into two broad categories:

(1) Models that use stand values as the basic modelling unit;

(2) Models that use individual trees as the basic modelling unit.

Whichever basic modelling unit they use, models considered in this paper have the same primary purpose: to provide an estimate of stand growth and yield for specified management regimes.

Stand models, regardless of the basic modelling unit, may be deterministic or stochastic. Stochastic models include random variables whose values are generated, whereas deterministic models do not. In past applications, practically all stand-level models have been deterministic, while most tree-level models have involved some random elements.

Stand-level Models

In the United States multiple linear-regression equations have often been used to predict growth and/or yield as a function of stand age, site index, and stand density. When yield is the dependent variable and growth is to be computed by differencing, an equation to project stand density (usually as a function of site index, initial age, and initial density) is also needed. Examples of multiple regression equations for predicting stand growth and/or yield include Wenger *et al.* (1958), Bennett *et al.* (1959), Brender (1960), Nelson and Brender (1963), Clutter (1963), and Burkhart *et al.* (1972). In the examples cited, growth or yield for the total stand, or for some merchantable portion of the stand, can be predicted; but information on volume distribution by size-class is not provided.

Lewis (1954) presented a series of alignment charts for estimating yield in unthinned radiata pine stands in New Zealand. In addition to information on the progress of height, basal area, and volume, stand and stock tables were also included. Yield prediction for radiata pine was extended to thinned stands by Beekhuis (1966). The method of yield prediction presented by Beekhuis differs from that of usual methods in that increments were plotted against height instead of age as the independent variable.

Stand models based on a diameter-distribution analysis procedure have been constructed in several recent studies (Bennett and Clutter, 1968; Lenhart and Clutter, 1971; Lenhart, 1972; Burkhart and Strub, 1974; Smalley and Bailey, 1974). In this approach, the number of trees per unit area in each diameter class is estimated, mean total tree-heights are predicted for trees of given diameters growing under given stand conditions, and volume per diameter class is calculated by using the predicted mean tree-heights and the midpoints of the diameter-class intervals and substituting into tree-volume equations.

Unit-area yield estimates are obtained by summing over diameter-classes of interest. Only overall stand values are needed as input, but fairly detailed stand-distribution information is obtainable as output. The radiata pine model presented by Clutter and Allison (1974) is a modification of the general diameter-distribution analysis procedure outlined above.

Tree-level Models

Stand models which use individual trees as the basic unit may be separated into two groups: models for which inter-tree distances are not required (distance-independent), and models for which inter-tree distances are required (distance-dependent) (Munro, 1974). In distance-independent models the growth of individual trees is a function of variables such as present size, site index, and stand density. Tree mortality in these models may be predicted from past growth rates or it may be generated randomly. A wide variety of approaches has been taken in the construction of individual-tree distance-independent models and it is difficult to portray a general outline of them; however, the model of Lemmon and Schumacher (1962) and that of Stage (1973) provide examples of this approach.

Distance-dependent individual-tree models that have been implemented vary in detail but are quite similar in overall concept and structure. Initial data of a stand are input or generated and each tree is assigned a co-ordinate location.

Increment for each tree is calculated (generally annually) as a function of its size, the site quality, and some function of distance to and size of neighbours which serves as an expression of competition. Growth is commonly adjusted by random elements representing genetic and/or microsite variability. Probability of tree death can be expressed as a function of "competition" and/or the individual tree's characteristics. Conventional stand characteristics are tabulated and available as output at specified intervals. Models of this general type have been produced by Newnham and Smith (1964), Arney (1974), Ek and Monserud (1974), Hegyi (1974), Lin (1974), Daniels and Burkhart (1975), Mitchell (1975), and others.

Selecting an Appropriate Modelling Approach

The modelling alternatives discussed are part of a continuum of complementary systems; they are not mutually exclusive options. Modelling alternatives can be evaluated only in light of the uses that will be made of the information. Decisions for which a large amount of stand detail is needed will require one approach, whereas other approaches will probably be most satisfactory for decisions which do not require detailed information about individual stands. An example of a management planning system which utilises growth models with varying degrees of detail is the CARP (Computer Assisted Resource Planning) System that is being developed in Canada (Glew *et al.*, 1976). To take advantage of the merits of different approaches to stand modelling, a compatible system of growth simulators — ranging from simple yield functions to models based on individual trees — was designed as an integral part of CARP.

In many circumstances detailed stand data will be needed. However, for situations that necessitate only aggregate stand information, simple functions will probably prove most efficient. It is possible to fit simple functions to points generated from repeated execution of complex models and to use these functions as input for other applications. When using the diameter-distribution analysis procedure described here, calculating volume per diameter class and summing to obtain a per-unit-area figure involves needlessly detailed computations if only an aggregate per-unit-area volume is desired. Strub and Burkhart (1975) derived a method for eliminating diameter-class interval computations when estimating stand yields, thus allowing a direct estimate of overall yield to be computed.

One cannot ascribe "advantages" or "disadvantages" to different modelling approaches except in the context of specific uses. However, the general characteristics of the various alternatives can be briefly reviewed. Stand-level models can generally be applied with existing inventory data, and are computationally simpler than tree-level models. Yield functions are inflexible for analysing alternative product mixes but a diameter-distribution prediction procedure overcomes many of these difficulties. All stand-level models are somewhat inflexible for analysing a wide range of stand treatments and are not likely to give reliable results outside the range of conditions included in the sample plots on which they are based.

Tree-level models are usually more difficult to apply with existing inventory data and they generally require more sophisticated computing systems than stand-level models. Because of the detailed information provided, alternative product mixes are readily evaluated with models that use individual trees as the basic unit. Of the stand-modelling options considered here, distance-dependent individual-tree models are more expensive to develop and operate than the other approaches but they offer maximum flexibility for analysing a broad range of treatment alternatives and, if logically constructed, are more likely to extrapolate well for conditions not included in the basic data.

Cultural treatment effects have been studied as part of the development of most tree-level models. Thinning options are invariably included in distance-dependent models because it is believed that response to thinning will follow directly from the competition relationships included. Use of competition relationships allows assessment of a wide range of thinning alternatives without the time and expense of replicating a large number of thinning plots. However, to date, rigorous evaluations of the accuracy and precision of thinning responses from the majority of these models have not been completed.

Response to factors such as fertiliser application, defoliation, and planting progeny of genetically selected trees has been analysed in various tree-level stand-simulation studies. Unfortunately the lack of adequate stand data has precluded in-depth evaluations of the adequacy of the models to reflect accurately stand-level response. However, in most trials the response to simulated treatments has been logical and compatible with expected response.

For many uses only predicted means are desired, and for these deterministic models are appropriate. In situations where the variability likely to be experienced in stand response and yields is required, stochastic models are needed. Additional computational difficulty and expense are generally involved in models which include random variability.

Additional information on general aspects of stand modelling is provided in papers by Curtis (1972), Munro (1974), Burkhart (1975), and Hegyi (1975).

DATA BASES FOR STAND MODELLING

It is rarely feasible to base stand models on repeated measurements of the same stands over an entire rotation. Periodic short-term measurements of growth from permanent plots distributed across the range of sites, ages, and stand treatments of interest provide a practical basis for developing prediction equations. Permanent plots provide excellent information for the stand conditions included in the sample. The disadvantages are the high cost of plot establishment and measurement, the delay in obtaining information, and changes in management practices and objectives over long periods of time.

Temporary plots can be used effectively to formulate variable-density yield tables (Vuokila, 1965), and they can provide valuable data for calibrating and validating stand models. The employment of temporary plots has cost advantages but suffers from the disadvantage that prediction of changes within stands is difficult with these types of data.

Trials that are properly designed and replicated are ideal for estimating parameters in growth models. When extremes of treatments are included, parameter estimates are more reliable. If parameter estimation or response to treatment trends is the primary objective of a trial, it is essential that the extremes of treatments and as many treatment levels as possible be included. The size of trials must generally be limited because of cost, variability of site, or paucity of experimental material. In these circumstances, hypothesis testing by analysis of variance has traditionally involved a small number of treatments and a large number of replicates. Such an allocation of resources is not efficient, however, when estimation of response to treatment trends is the primary objective.

Although trials provide excellent data for estimating parameters, a small number of intensively measured trials may not be representative of the entire population of interest. Sample plots, which may not be as intensively measured or monitored as trials, should be established throughout the range of growing conditions to verify and check growth projection equations. Models cannot be satisfactorily validated with the data used in their construction; sample plots, both permanent and temporary, are valuable sources of independent data.

Stem analysis, which involves determining past growth by measuring the accumulated stem increments of sample trees, can be effectively employed for gathering growth data. Information from stem analyses is often valuable for supplementing and extending plot records.

Individual tree studies can aid in the construction of stand models. Analysis of growth of open-grown trees allows incorporation of upper limits of certain growth parameters and enables study of growth relationships without the confounding of variations in stand structure. Such limits can act as constraints that help ensure logical model behaviour under extreme conditions. Single tree plots in stands have been found to be efficient for gathering data for stand models that use individual trees as a basic unit.

As stand models become more detailed, research results from all areas of forest biology — silviculture, genetics, physiology, nutrition, water relations, and so on — are potential input. Computerised models of tree growth and stand dynamics can aid in integrating and synthesising existing knowledge. Simulation models are valuable for identifying knowledge gaps and critical areas for new research.

Relatively little attention has been devoted to efficient designs for obtaining stand modelling data. The need for data from silvicultural experiments for growth modelling was discussed by Wright (1976). Ek and Burkhart (1976) presented views on the inherent links between forest inventory, stand modelling, and evaluation of silvicultural alternatives.

STAND MODELS FOR RADIATA PINE

Reliable stand projection systems are essential for radiata pine because of its importance for both domestic and export markets, and because of the variety and intensity of cultural treatments applied in its management. National and regional development planning will surely emphasise the significant role of radiata pine, thus necessitating efficient forecasts of wood availability for large areas. At the other end of the spectrum, decisions must be made about management of individual stands now in production, and of future stands. Evaluation of thinning, pruning, fertiliser application, and other treatment options requires detailed information about wood quantities by size and quality classes.

Fortunately, relatively large numbers of permanent sample plots have been maintained in radiata pine stands in New Zealand. These sample plots provide an excellent basis for developing models which should adequately reflect stand development for those conditions included in the data. The presently available plot observations can be used for constructing models, based on overall stand values, for diameter distribution analyses and for distance-independent individual-tree models — which should be valuable components of a system of stand models for use in radiata pine management.

Management practices and utilisation standards are changing rapidly, however, and highly flexible models are needed which can be used to predict yields from stands managed in ways as yet undocumented in actual stands. Use of stand models in dynamic management situations will, by necessity, involve some extrapolation to conditions not included in the basic data. To provide accurate predictions for a wide range of regimes, stand models must be logically constrained and structured. In my opinion, logical behaviour of stand models over a broad range of conditions is most likely to be accomplished by constraining individual-tree growth parameters and structuring logical interactions in tree-level models. Thus, in addition to using existing plot records to develop prediction equations, I feel that considerable resources should be allocated to structuring biologically rational models of radiata pine tree growth and stand dynamics.

As stand models are developed, gaps in knowledge and weaknesses in the available data will inevitably be revealed. These can be used to identify relevant research projects and to design future plot installations.

CONCLUSIONS

Many different types of information of varying degrees of detail are needed in management systems for intensively cultured species such as radiata pine in New Zealand. It will surely require a combination of several techniques to solve these complex and challenging stand-modelling problems.

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