Growth & Yield in British Columbia
Background and discussion

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1 Introduction

This is a first attempt at reviewing the status and issues confronting growth and yield modelling in British Columbia. It may be considered as a discussion paper, with the purpose of indicating my initial impressions of the current situation and research needs, and of eliciting further comment. Suggested research avenues are thought mainly in relation to activities to be performed by the Chair, and do not necessarily cover work more appropriately or currently carried out by other organizations or individuals. For instance, little is said about measurement and establishment of permanent sample plots, site quality assessment, or the maintenance and enhancement of existing models.

The forestry sector outlook is briefly analyzed first, to provide a framework for present and future requirements. Then there is an outline of some concepts and terminology necessary for the subsequent material. A discussion of past and present BC growth models comes next, followed by comments on various issues concerning approaches and research needs. Finally, the main points are summarized.

2 The forestry environment

Forestry and the forest products industry are one of the most important components of BC's economy. Apart from the economics, there is increasing interest in the environmental, recreational, cultural, and other aspects of the forests. Growth and yield models can be useful in connection with wildlife, conservation, etc. Accurate tree growth and yield prediction, however, is likely to be less critical for these applications than for timber management and planning. Extensions of timber-oriented models might be sufficient. Therefore, and also for reasons of ignorance, I will focus mainly on timber production.

Present harvest and estimated allowable cut in the province is about 70 million cubic metres per year, down from 80 million ten years ago. The long-term sustainable cut is estimated at 50 to 60 million. A reduction in quality and value can also be expected, as the proportion of large piece sizes and more valuable species decreases.

In principle, current production levels could be maintained through an intensification of forest management, including spacing and thinning, fertilization, tree improvement, forest health measures, and hardwood management. Value-added processing could help in maintaining employment and revenues. Regardless of the degree of achievement of these goals, it is clear that the period of expansion is largely over, and major structural changes can be anticipated. As the transition from old-growth to second-growth occurs, the forest industry will retool for smaller log sizes and a different species mix. The pulp and paper industry may move from an almost total reliance on sawmill residues to the utilization of roundwood from thinnings and small trees. Logging and silviculture will change, together with growth and yield prediction needs and priorities.

According to the *Forest, Range and Recreation Resource Analysis* (MOF, 1994), the area in millions of hectares by species groups was: pines 15 (26%), spruces 14 (25%), true firs 9 (16%), deciduous 5 (9%), Douglas-fir 4 (8%), hemlocks 4 (7%), cedars 2 (4%). A 57% of productive TSA forest land was in pines (13 million hectares, mainly lodgepole), and spruces (8 million hectares, mainly white and hybrid). Timber production over 1984-1994, in million of cubic metres per year, was: lodgepole pine 19 (24%), spruce 17 (21%), hemlock 14 (17%), true firs 11 (13%), others 23%. Both in area and in production, pine had increased surpassing spruce, a trend that is expected to continue.

Clearcutting was 90% of the approximately 200 thousand hectares harvested, the rest included seed-tree, shelterwood, and selection cutting. Juvenile spacing was carried out in 45 thousand hectares in 1992-93, mostly in the Caribou Forest Region in relation with lodgepole pine repression. Pruning and commercial thinning were negligible, although MOF projected that in 10 years 10% of the volume would come from production thinning.

In regeneration, there has been an increasing trend toward planting, going from 50% in 1988 to 65% in 1992-93 (about 180 thousand hectares per year), mostly lodgepole pine and spruce.

3 Growth modelling fundamentals

Growth and yield models (or simply growth models, growth and yield is somewhat redundant), are vitally important in forest management. Typical uses of their predictions of stand development are in: (a) long-term forest planning, (b) evaluation of thinning regimes, (c) updating of forest inventories.

The earliest examples are the classical "yield tables", relationships describing the expected course over time of volume, height, diameter, and possibly other variables. Already in the eighteenth century foresters discovered that it was not necessary to wait for a full rotation; techniques were developed for estimating these trends from shorter observation intervals in a number of different stands of various ages (cross-sectional or panel data). Yield tables, these days more often described by mathematical equations, are still widely used. For instance, VDYP in British Columbia.

Although yield tables are adequate for many purposes, especially in unmanaged natural stands, more flexibility is desirable in other situations. Thinning treatments, for example, cannot be properly represented. Even without treatments, ad-hoc procedures of doubtful rationality are needed to project existing stands that have deviated from the standard curve. *Dynamic models* are more appropriate under those conditions.

Many kinds of dynamic models have been developed or proposed. Although only slowly gaining acceptance in forestry, system theoretical concepts, long time standard in physics, engineering, and other disciplines, can aid in clarifying the conceptual basis of different growth model types, and in ensuring their soundness. The basic idea is not attempting to develop directly the trend of variables over time, as in yield tables. Rather, the *state* of a stand at a point in time is described by a certain number of variables, and equations are obtained to predict the rate of change over time of this state. Given an initial state, these rates can be accumulated, or iterated, to compute the future state trajectory. A thinning produces an instantaneous change of state, and the projection can then be resumed from the new state.

Different model types differ essentially in the level of detail represented in the state description. *Individual-tree distance-dependent* models, e.g. TASS, are the most detailed. The stand is described by the ground coordinates, diameter, and sometimes height and other variables, for each tree in a stand or plot. The model predicts the rate of change in these variables (growth rate), as a function of the current value of all (or some) of them. A rate or probability of mortality is also estimated.

Individual-tree distance-independent models are similar, except that tree coordinates are not used. A list of tree diameters, and possibly heights, etc., describe the stand, but spatial relationships are ignored. Examples in B.C. are Prognosis and MGM.

The third type of growth models in the usual classification are the *stand-level*, or *whole-stand* models. Here, the stand at each point in time is described by a relatively small number of aggregate variables, e.g., top height, basal area, trees per hectare. The new VDYP7 is of this kind. Stand density management diagrams may be seen also as a simple instance of stand-level model.

4 BC Growth models

Early growth modelling developments in B.C., are well-known around the world. Among others, Warrack's 1959 report on thinning in Douglas-fir is remarkable. After some initial work by Staebler in the US in the 1950's, it was Newnham, starting with his 1964 PhD thesis at UBC, who introduced and popularized distance-dependent models. Many similar models followed, including the UBC PhD theses of Bella (1971), and Arney (1972). After a first version for spruce at Yale, Ken Mitchell developed the Douglas-fir model later known as TASS, published in 1975, while working for the Canadian Forest Service in Victoria. This is a highly detailed distance-dependent model, including modelling of branch growth and stem profiles, worldwide considered as a classic. Goulding (1972) constructed one of the first distance-independent models, in yet another UBC PhD thesis. Partly based on Goulding's work, in 1974 Munro published a paper proposing the model classification presented above (although not exactly in those terms), which has become a standard reference.

After that initial flurry of activity things became quieter, apparently dominated by developments and application of TASS and its extensions. TIPSY, essentially a mechanization of the TASS-generated yield tables published by Mitchell and Cameron in 1985, made TASS usage more accessible. The MOF Resource Inventory Branch VDYP "static" yield table is usually preferred for unmanaged natural stands. These two models have been the standard growth and yield prediction tools in BC for many years.

Based on TASS output, Craig Farnden built a series of graphical models, Stand Density Management Diagrams (SDMDs). Another development was the Canadian Forest Service's STIM, a hybrid with distance-independent and stand-level features. This model seems orphaned, however, with no support, promotion, nor further development.

More recently, two diameter-driven distance-independent models have been introduced to fill a perceived vacuum in the modelling of "complex" stands (mixed species, uneven-aged). These are Prognosis BC, an adaptation of the US Forest Service Forest Vegetation Simulator (FVS, previously known as Prognosis), and a version of MGM, an aspen/spruce mixewood model from the University of Alberta.

Under development by Jim Flewelling and the Resource Inventory Branch is VDYP7. Despite sharing the name with VDYP (or VDYP6), this is a true dynamic model, at the stand-level. It is, however, being fitted with data from natural unmanaged stands.

It may be mentioned also the related issue of site quality assessment. Site classification is both a pre-requisite and, in the case of methods based on height growth, a special instance and a component of growth models. Site index curves, growth-intercept, and related methods are the most precise when appropriate trees are present. Indirect adjustments and ecological classification have been used for deforested land, uneven-aged stands, or other situations where height-age relationships are inapplicable or unreliable.

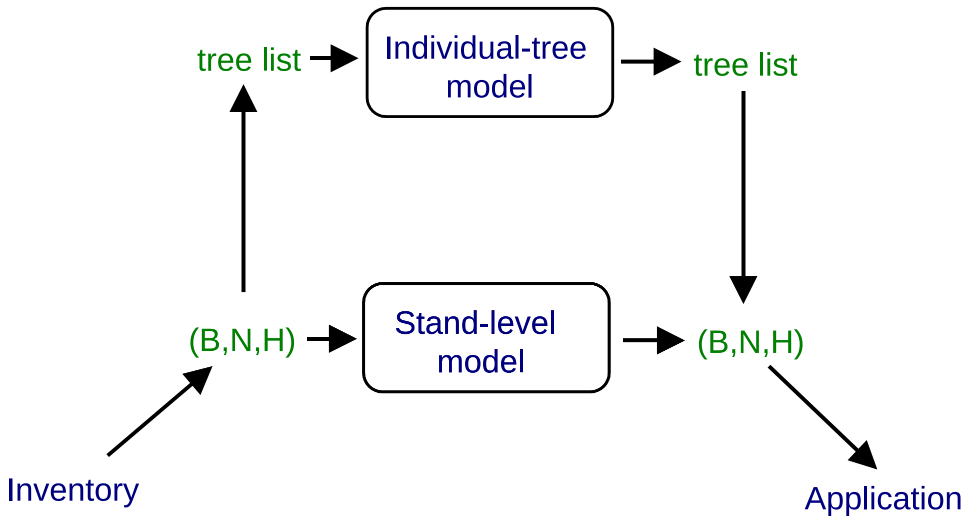
5 Problems, needs, and prospects

The achievements in growth modelling in British Columbia are impressive, and many of those involved in this effort are highly capable and widely respected. As always, there are limitations and room for improvement. I focus here on what I see as problems and areas where further work is needed. Many of these issues are not unique to BC, but general methodological or conceptual research problems not yet satisfactorily resolved. Some are controversial, and this discussion reflects largely my own opinions and biases.

One of these controversial issues is the appropriate level of resolution for growth models. That is, the type of model in Munro's classification (stand-level, distance-independent, distance-dependent), and various levels of detail within these. The degree to which a model is mechanistic or empirical is often linked to this; in fact, it is not necessarily so, and I will comment on that later.

Discussion usually centres on the advantages of detailed models in being more realistic and providing more information, and their disadvantages of overparametrization and uncertainty in the parameter values. More important, however, is uncertainty in the initial state. An individual-tree model assumes knowledge of the size of every single tree in the stand. This is rarely the case. Forest inventories can provide only very crude estimates of diameter distributions (or "tree lists"), and more often only acceptable estimates for stand-level aggregate variables such as trees per hectare, basal area, stand height, or volume per hectare. Tree coordinates are not usually available. Even if some diameter distribution is obtained, this is an aggregate at the stand or compartment level, which can be very different from the short-range distribution for neighbouring trees on which models are based (there are, in fact, unsolved problems relating to what a distribution really means when there are spatial interactions).

In practice most of the time, therefore, using an individual-tree (or *tree-level*) model for projecting an existing stand involves artificially generating a detailed initial state from the knowledge of a few stand-level variables. Various "tree list generation" procedures have been proposed to this effect. The situation is depicted in the following figure where, as an example, basal area, trees per hectare and top height (B, N, H) are shown as the known/estimated stand variables, and a simple diameter-driven distance-independent model is assumed. The current values of the stand variables are used to generate the initial state required by the growth model. The model projects this state to some future time, and the information is then summarized for its use in decision making.



If a tree list can be reliably generated from stand-level information, then clearly that additional detail is redundant, and in principle it should be possible to project the stand variables directly with a stand-level model. If on the contrary, the detailed tree-level information is crucial, as in some complex stand types, it must be accepted that no data manipulation will be able to reliably predict the future of a stand if its current state is not accurately known.

Where applicable, good stand-level models have many advantages, in terms of precision, data requirements, ease of use, etc. Even then, there may be justification for the use of tree-level models in those circumstances, at least as an interim measure. A tree-level model may be the only one available. It is easier to build a plausible individual-tree model with little or no data, possibly the situation in the early days of TASS. Mechanistic models of this kind provide valuable insights on stand dynamics. Good stand-level models are more difficult to obtain. Note however, that the often claimed advantages of individual-tree models in predicting size distributions and other detailed information does not hold in this instance; if a distribution can be generated from the initial stand variables, it can also be generated from the final ones.

At this stage in BC, it seems advisable to work toward the development of accurate data-based stand-level models for "simple" stands. The popularity of SDMDs has demonstrated a demand for simpler growth prediction tools, relatively easier to use and understand. SDMDs attempt to describe stand development in a two-dimensional state space (or with a pair of two-dimensional projections). Although convenient for graphical representation, in their current form this is insufficient for accurate predictions. It should be possible, however, to build appropriate models with three or four state variables. VDYP7 is a step in the right direction, although limited at present to natural stands. These models will become increasingly important as needs grow for the analysis of silvicultural options in the second-growth forests.

In complex, uneven-aged and multi-species stands, the use of tree-level models is probably unavoidable, at least with our current level of knowledge. Their state information requirements mean that usually their prediction accuracy will be rather limited. In addition, errors and uncertainty accumulates, affecting the model suitability for long-term projections (Prognosis BC, for instance, is not recommended for projections longer than 50 years). Nevertheless, they can be useful in understanding the behaviour, species dynamics and response to treatments in these forests, even if mostly qualitatively.

Diameter-driven models like Prognosis and MGM, however, may not be the best answer in the long term, although they can fill an immediate need. Trees do not grow faster because they are thicker, they are thicker because they have been growing faster. There is often a strong relationship between the two, especially in natural or semi-natural stands where most of the work has been done. But once a stand is intervened, e.g., removing competitors of a tree, that correlation is broken, and without the right cause-effect link the model performance will suffer. Models based on growing space, like TASS, are probably a better option.

There are still many fundamental question in the functioning of complex stands and models that need to be investigated. Things like the relationship between distributions and spatial pattern, the modelling of spatial interactions and the consequences of ignoring them in distance-independent models (the suitability of what is known as the "mean field approximation" in physics), alternative ways of approximating these interactions (pair approximations, moment methods), numerical stability and chaos in simulation computations, aggregation techniques, etc. The mathematics can be forbidding and few forest researchers are approaching these problems, but their resolution is necessary for further progress.

There is a continuing debate between proponents and detractors of empirical and of mechanistic ("process") models. Actually, a whole range of models is necessary, supporting different needs and feeding from each other. It is desirable for all models to have some theoretical basis, in the sense of producing biologically meaningful responses and behaving reasonably when extrapolated. Models more mechanistic are needed when there is little data, and when the objectives emphasize the understanding. Models more empirical are appropriate when data is more abundant, and where the emphasis is on precision in practical management predictions. Ideally, knowledge acquired from one model will aid in the improvement of others at different stages.

It is important, however, whenever possible to check assumptions against real data. There is a trend in some quarters to run too far ahead of the data. Models become ends in themselves, complex conglomerates of hypotheses and assumptions with little basis on reality. Experience shows that observations rarely agree with preconceived ideas, and relying on theories without testing them at every step of the way is risky.

More effort is needed in BC to collect, assemble and evaluate growth information. Especially for managed stands, there seem to be data and permanent sample plots falling through institutional cracks in between groups that tend to deal mostly with designed experiments or with other kind of stands. Models should utilize all the available information through proper parameter estimation procedures, and not rely on *ad hoc* adjustments or "calibration" with partial data sets. Research on new stem analysis procedures, band dendrometers, and other techniques for accelerated data acquisition could be useful.

Models need to be open, well documented, with more emphasis on their relationships and equations than on the details of a particular computer implementation. "Brand naming" should be avoided: a model must be a work in progress, adaptive, never finished; at every stage it must be possible to put together the best ideas and components from different sources. Related to this, from an efficiency point of view it would be generally preferable to build, instead of monolithic integrated programs, systems with separate modules for elements such as growth, volume, waste and decay, economic analysis, etc., communicating through intermediate files or other means. In this way components can be easily updated or replaced, and a "mix and match" of the most appropriate models for a particular application becomes possible.

6 Summary and conclusions

British Columbia is entering a transition from the exploitation of old-growth forests to a reliance on second-growth stands. These stands will be considerably different from the old ones; many are being planted, and it is likely that at least some will be managed in a more or less intensive basis. Lodgepole pine and white and hybrid spruce will form a major part of the resource. Hardwoods are also expected to increase in importance, in mixture with conifers, and possibly also as pure stands. A variety of other forest types will be locally important. New management options, together with a tightening supply situation, will require models capable of accurately predicting growth and response to a variety of treatments. Improvements are also desirable in predictions for the stands to be harvested during the transition.

Growth and yield has a long tradition in BC, and much of the early work is internationally well-known. A number of models are currently available, mostly of the individual-tree type. There is still, however, a strong need for improved growth and yield forecasting.

Without neglecting current work, it seems desirable to initiate development of new simpler models for simple stands, and of more complex models for complex stands. Some fundamental research on theoretical and methodological modelling issues is also needed, especially in relation to the modelling of uneven-aged and mixed species forests.

The availability and quality of PSP data should be reviewed, in particular for managed stands.