GROWTH MODELLING AND YIELD PREDICTION FOR SUSTAINABLE FOREST MANAGEMENT

by

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Summary

A brief synthesis of milestones in forest growth modelling helps to establish research topics for further model development in managed tropical forests. Forest growth models have become indispensable for forest management, but need further development to realize their full utility. Feedback from monitoring predictions versus realizations should provide the basis for continuing improvement, both in growth modelling and in forest management.

Introduction

Foresters have been using various kinds of growth model for at least two hundred years. Notable milestones in the development of modern growth models include the compilation of experience tables (e.g., Hartig 1795), arithmetic growth formulae (e.g., Schneider 1853), alignment charts (Reineke 1927), biologically-based growth formulae (Schumacher 1939, Bertalanffy 1941), statistically-derived growth equations (MacKinney and Chaiken 1939), matrix models (Leslie 1945, Usher 1966), compatible growth and yield equations (Buckman 1962, Clutter 1963), and computer-based individual tree models (Newnham 1964, Newnham and Smith 1964). The state-of-the art has been reported in several conferences (e.g., Fries 1974, Ek *et al.* 1988, Wan Razali *et al.* 1989, Vanclay et al 1993, Foli *et al.* 1997, Amaro and Tome 1997, LeMay and Marshall 2001), and much of the accumulated knowledge is summarized in two key texts (Alder 1995, Vanclay 1994a). A small number of models continue to be particularly influential because of their longevity or the many variants they have spawned (e.g., JABOWA, Botkin *et al.* 1972, Botkin 1993, Prognosis Stage 1973, Sterba and Monserud 1997, FREP, Hahn and Leary 1979, Miner *et al.* 1988, NORM, Vanclay 1989, 1994a,b, Ong and Kleine 1995, Sortie, Pacala *et al.* 1993, Deutschman *et al.* 1997). What then remains to address in this symposium?

Much of the pioneering research in forest growth modelling has addressed plantations and temperate forests, both of which avoid many of the complexities of tropical moist forest. Challenges in the tropics include many species, a large range of stem sizes and shapes, the absence of reliable annual rings. Solutions to these issues have been proposed (e.g., Vanclay 1994a, Alder *et al.* 2002), but scope remains for further refinement and for implementation in forest management.

Many models, especially those with nice graphics, tend to emphasize dynamics at the stand level, and are not easily scaled-up to the estate level. The issues for forest managers are about stem sizes, silvicultural systems (Kleine 1997) and sustainable yields at the estate level (Vanclay 1994b). These requirements are not always congruent with

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particular species (e.g., JABOWA, Botkin 1993), or with physiologically-based models the objectives of ecologically-oriented models focussing on the presence or absence of focussing on biomass accumulation (e.g., 3PG, Landsberg and Waring 1997). There is still a clear need to further develop established modelling techniques to meet the challenges of the tropics, and to apply them to contribute to better management of tropical forests.

Why model?

There are many good reasons for building models. It is useful to draw a distinction between models for understanding and models for prediction (Bunnell 1989). Building a model can help to analyze data from experiments and observation plots. It can help to synthesize and communicate existing knowledge and to identify gaps in our understanding. It can help to focus research plans and to anticipate results, so that measurement programmes and techniques can be planned accordingly. Modelling may be the most efficient way to examine experimental data, investigate implications and formulate optimal silvicultural guidelines. However, one of the most enduring uses of modelling in forestry is for growth and yield prediction.

Reliable yield predictions are simply essential for sustainable forest management. Efficient harvest planning requires predictions of when, where and how much timber can be harvested. Inferences about sustainability can only be made if we can anticipate when the next harvest can be expected. Clearly, yield predictions are critical for efficient management of regrowth forests, in policy formulation, in strategic planning, and in operations management.

These requirements have implications for model design, implementation and use. Reliable predictions depend on reliable models and reliable input data. The old adage, "garbage in, garbage out" applies equally to forest growth modelling. However, it is not only the data, but the context for the data. Reliable inferencing requires an appropriate user interface, so that users can be confident about using a model correctly, and understand the data requirements and the results produced. It also requires that models generate predictions in a convenient form, amenable to further processing or for reporting and presentation. Thus the utility of a model cannot be gauged without an understanding of who uses the model, what they use it for, and what other systems are involved.

Perhaps the most compelling reason for formally constructing a growth model and building a yield prediction system is that it provides an explicit account of the many items and exclusions involved in a yield prediction. Vanclay (1996) offered a check-list of issues to be addressed in a yield prediction:

1. Are area estimates reliable and repeatable?
2. Have due allowances been made for inaccessible and unproductive areas?
3. Do they exclude stream buffers, difficult terrain and protected trees?
4. Has the area been stratified to reduce within-stratum variance?
5. Do growth estimates take realistic account of site and species differences?
6. Has due allowance been made for mortality and deterioration of merchantable stems?
7. Is the harvesting model consistent with field practice?
8. What allowance is made for breakage and for defective stems?

9. Has due allowance been made for damage to the residual stand?
10. Are the volume equations appropriate for the stands in question?
11. Do volume equations allow for defect included in logs?
12. Are the cutting cycle and the timing of harvests realistic?
13. Are all assumptions clearly stated?
14. Is the Allowable Cut applied in a way that will achieve the desired objectives?

Each of these issues may involve several items. Coarse "rule-of-thumb" approaches to yield estimation (e.g., assuming 5 m^3/ha/year over 100,000 ha) make it difficult or impossible to establish whether all of these factors have been taken into account, with the result that "guestimates" tend to overestimate yields. In contrast, systematic approaches based on growth models usually to offer more rigorous estimates that can be itemized and tested item-by-item, allowing systematic improvements to be made.

New Techniques for Model Development

Two books (Alder 1995, Vanclay 1994a) explain much of the art and science of model-building for growth and yield prediction, but the relentless march of technology means that there is always something new. New developments in three areas warrant a mention.

MYRLIN (Methods of Yield Regulation with Limited Information, Alder et al 2002) offers useful guidance for yield prediction in tropical forests. The underlying thesis is that diameter increment patterns for tropical forest species have broad similarities from region to region, allowing general assumptions to be made about growth rates. Selected case studies demonstrate the utility of grouping species using an ordination of the species mean increment on its typical size as given by the 95% point on the cumulative diameter distribution. This allows each species to be represented as a point on a graph, with mean increment on the y-axis, and 95% diameter on the x-axis (Figure 1). This provides an efficient basis for combining many species into a tractable number of groups for model development. These case studies in several tropical regions support the notion of pan-tropical groups that may form the basis for regional comparisons of growth and dynamics (Alder *et al.* 2002).

Equations used to predict diameter increment, mortality and other changes in the forest should be statistically based, with due consideration for the errors involved, because these equations are applied repeatedly, allowing errors to accumulate. While the principles of least-squares regression analysis remain unchanged, the mechanics of fitting regression lines have changed dramatically in recent years, so that statistics should no longer be an obstacle. Modern statistics packages are easy to use and understand, offer good diagnostics, and encourage graphical exploration of the goodness of fit and the nature of the residuals (e.g., Vanclay 2002a, Cook and Weisberg 1999).

Two statistics packages, available freely via the internet, are noteworthy. One of these, CurveExpert, takes the effort out of fitting a curve to (X, Y) pairs of data. It automatically fits and compares 35 built-in regression models and up to 15 additional user-defined models (Figure 2). CurveExpert has some limitations: it can use only pairs of data (i.e., only one independent variable), it does not provide standard errors of the estimated

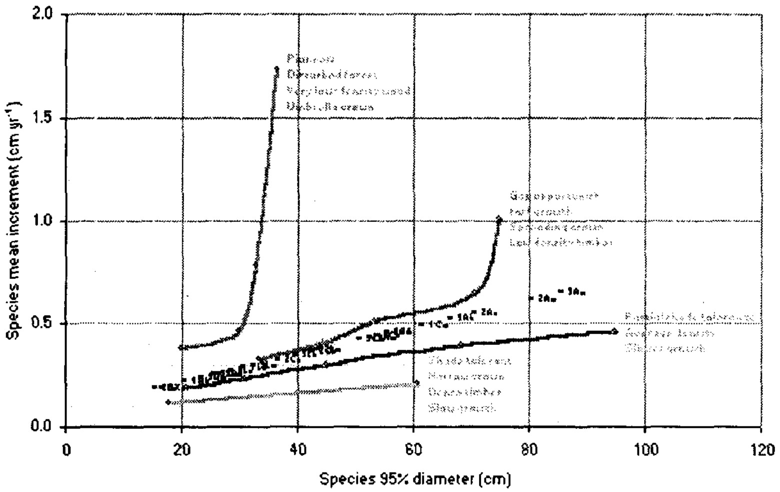

Figure 1. **Approach used in MYRLIN to classify species on the basis of size attained and average growth rate (Alder *et al.* 2002).**

parameters, and does not facilitate analysis of residuals. However, it is a convenient way to quickly screen data to see what relationships warrant further investigation with a more capable statistics package. CurveExpert is shareware developed by Daniel Hyams, and is available via the internet at www.ebicom.net/~dhyams/cvxpt.htm.

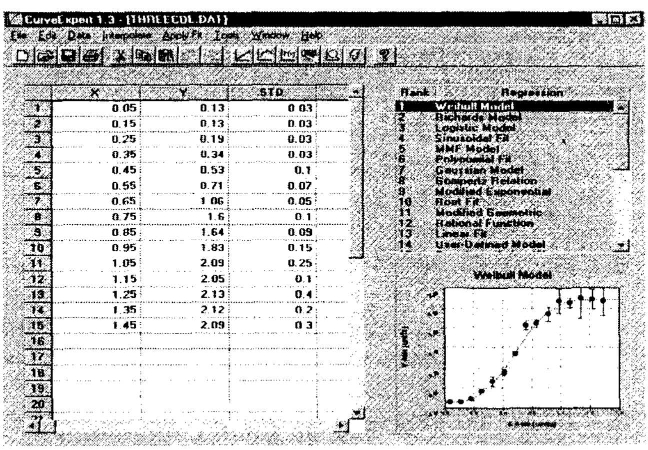

Figure 2. Screen image of CurveExpert.

ARC (Applied Regression and Computing, Cook and Weisberg 1999) is a powerful statistics package that offers several innovative tools to encourage thorough analysis and insightful scrutiny of data. Pull-down menus guide the user through regression analyses, encourage graphical exploration of the fitted relationship and residuals, and provide a range of diagnostics. ARC is available freely from the web at www.stat.umn.edu/arc, but the book (Cook and Weisberg 1999) may be needed to realize the full capabilities of the package. New statistics packages like CurveExpert, ARC and others (Vanclay 2001) are cheap (or free), easy to use, more powerful and offer better insights than the packages of a few years ago. The effort spent learning one of these packages will be well rewarded through increased productivity and new insights.

Most modellers are familiar with the situation that the concept for a model, the data preparation and the statistical analysis represents only half the work of building a model. The other half involves implementing the model on a computer, often a solitary task involving lots of computer code (in Fortran, C or Visual Basic) incomprehensible to others. It need not be so. New modelling environments such as Stella and Simile make it easier to implement models more quickly, in a way more accessible to others. Simile (Muetzelfeldt and Taylor 2001a,b) was especially designed for forestry applications, and offers several useful features for modelling forest growth. Like other systems dynamic software, the diagrammatic representation used in Simile replaces the code and serves as the documentation (Figure 3), thus avoiding the all too common problem that the code, flowchart and documentation diverge and become ambiguous or contradictory. However,

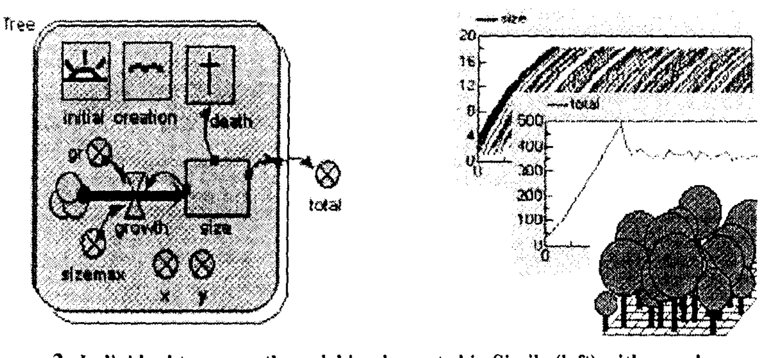

Figure 3. **Individual tree growth model implemented in Simile (left) with sample output from model run (right). From the Simile website at www.ierm.ed.ac.uk/simile/gallery/**

unlike other systems-dynamic platforms, Simile combines the best elements of systems dynamics and object-oriented programming, providing capabilities particularly useful in growth modelling (e.g., multiple instance submodels; the ability to dynamically create and destroy submodels). Some of the more generic features provided by Simile are particularly innovative (Muetzelfeldt and Taylor 2001a,b):

- Simile can generate hypertext descriptions of a model, allowing users to navigate a text representation of a model with a standard internet browser;
- Moving the mouse over a Simile construct causes a pop-up window to

appear, revealing the contents (including constants and graphical relationships, any comments, and the current values);
- The "plug-and-play" feature of Simile facilitates the substitution of submodels (Simile or DLL), thus encouraging experimentation.

Other capabilities may be forthcoming: automatic generation of meta-submodels; automatic sensitivity testing; and model-specific tutorials generated by the software. These facilities should enhance the capabilities of models, make modellers more productive and empower them to be more innovative. Simile is available via the internet at www.ierm.ed.ac.uk/simile/ or at http://www.simulistics.com/products/simile.htm

Testing models

Procedures to test models are well-established (Buchman and Shifley 1983, Vanclay and Skovsgaard 1997), but few rigorous tests of models have been published (e.g., Soares et al 1995). It is important to test models, to establish their strengths and weaknesses, and to demonstrate to users the range of conditions over which reliable projections can be expected.

It is not necessary to establish that that a model is "perfect" - that is probably impossible because all models are abstractions of reality. But it is important to establish that the model is correctly implemented and free of gross errors, to define the domain of reasonable performance, and benchmark the model for selected stands to gauge the extent of any bias. Until a model is tested in this way, we should be cautious about using it to support long-term harvesting commitments or to support claims of sustainability.

Using models

Many models are under-utilized, used only by their builders, sometimes only until a thesis is completed (Vanclay 2002b). If such a model offers useful insights, such limited use may be sufficient to justify the development effort. Too often however, the full potential of a model is not realized, and too often another researcher re-invents the wheel, building a similar model with the same data for a similar purpose. In some ways, this is part of science: if an alternative viewpoint leads to the same conclusion, it lends credibility to the conclusion. However, the question is whether a "completed" model is the conclusion we seek, and whether the alternative approach is sufficiently different to constitute an independent viewpoint. It may be that a thorough evaluation of a model may do more to establish its credibility than this duplication of effort. Furthermore, the need for better information for forest management is such that we do not have the luxury to duplicate efforts. There is an urgent need for models to guide new insights into the management of regrowth forests.

The concept of an optimal stand structure is central to plantation management. Most forestry students are well versed in the procedures to establish the optimal initial stocking, thinning regime and rotation age of a monospecific plantation (e.g., Assmann 1961). Equivalent concepts of optimal stand structure for uneven-aged stands (e.g., reverse-J, de Liocourt 1898; sustainable diameter distribution, Adams and Ek 1974) are controversial (e.g., Smith 1992). There are few studies that attempt to establish the optimal stocking, stand structure, girth limits or harvesting regime for uneven-aged mixedspecied forests (e.g. Valsta 1993), and even fewer for tropical high forest (e.g., Vanclay 1989).

Estate-level modelling

The ultimate goal for many forest growth modellers is to see their models used in estate planning, to sequence harvests more efficiently, to allow alternatives to be evaluated in an objective way, and to allow a multiple objectives and diverse constraints to be accommodated. While this is becoming more common, especially in temperate forestry (e.g., Hof 1993), it remains the exception in the tropics (e.g., Vanclay 1994b), and warrants more attention. To realize this goal, growth models and other forest information systems must be compatible and constructed in a way that they can be linked efficiently. Geographic information systems, inventory databases, growth models, yield schedulers and optimizers need to communicate seamlessly so that data can be transferred efficiently between these systems.

An integrated systems-view of forest information of this kind offers additional indirect benefits. The overall quality of forest resource estimates usually depends on the weakest link in this chain, but this weak link rarely identified explicitly. Failure to identify this weak link means that effort and resources may be expended inefficiently by unnecessarily enhancing other system components that are already adequate (Vanclay and Turner 2001).

Studies of improved harvest scheduling tend to focus on the environmental benefits that can be attained rather than the additional timber yields that can be realized. The additional timber that can be obtained may be significant, because the use of an optimizer ensures that all stands are harvested when they are "ripe" and that no stands are overlooked. However, an optimizer is not the only way to derive this benefit: a simple graphical analysis of the harvest schedule can gauge the optimality of a harvest provided that an optimal stand structure can be defined. Vanclay and Turner (2001) offered an example of such an analysis for the Wombat State Forest in Victoria (Australia), showing the proportion of the forest area retained in an over-mature condition, and the proportion of the harvest cut prematurely (Figure 4).

The way forward

Efficient forest management relies on information drawn from large amounts of data amassed through several different information systems. These systems and data must work in concert, for the goal of greater efficiency to be achieved. Great care is required to ensure that all components are accounted for, as overlooking one or more components may lead to an overestimate. Efficiency also requires that it is possible to judge, at least in broad terms, the accuracy of each system component. The best way to monitor system performance may be to prepare spatially-explicit predictions for analysis units approaching the scale of field management units (cf. compartments), so that predictions can be compared efficiently with realized outturn (Vanclay 1991). Ideally, such monitoring of predictions and realizations should become a routine process of performance monitoring. One should not expected that predictions will match the realization on each or any management unit, but the running average over several units should be close. Any discrepancy should alert forest managers to the possibility of bias in the prediction system, or lax supervision of field operations. Ultimately, the only reliable way to improve growth models and yield prediction systems, to maintain best-practice forestry standards, and achieve sustainable forest management, is to close this feedback loop.

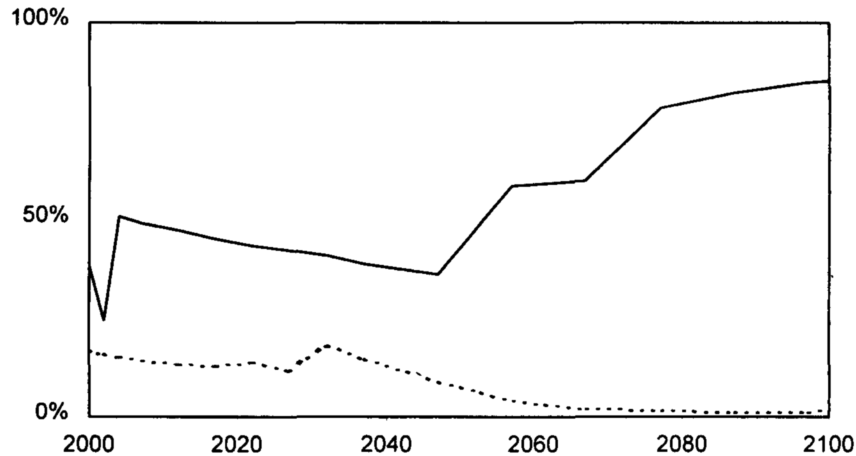

Figure 4. An evaluation of the harvest schedule for the Wombat Forest in Victoria, Australia. The upper, solid line reveals the extent to which harvested stands have attained the maximum MAI. The lower, dotted line indicates the proportion of the production estate with over-mature forest. Optimal scheduling in a regrowth forest should result in 100% of the maximum MAI and no over-mature forest within the production estate.

In Australia, on-going conflict between forest managers and environmental (non-government) organzations (ENGOs) has led to mutual distrust, and a situation where the ENGOs and some politicians will not reality accept the results of monitoring by the forest service. In such situations, an independent yardstick may provide an impartial basis for performance evaluation and can help to heal the distrust. One alternative, independent yardstick suggested by Vanclay and Turner (2001) was to estimate the lower 95% confidence interval of the growing stock using current inventory. Such a yardstick could easily be checked, or derived independently by ENGOs, but retains the possibility that the forest service could manage the resource more aggressively during periods of high timber prices by increasing the intensity of inventory.

Conclusion

Forest growth models have become an indispensable tool for forest management. Clearly, models are useful, but they could be more useful. To realize their full utility, models need to become more accurate, and need to become an integral part of the forest management system. Model predictions should be monitored to reveal any discrepancies between predicted and realized outturn. This feedback loop provides the basis for a system of continual improvement both in growth modelling and in forest management.

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