Forest growth and yield modeling

Forest growth models attempt to quantify the growth of a forest, and are commonly used for two principal purposes: to predict the future status of a forest and the nature of any harvests from that forest, and to help consider alternative cultivation practices. Models may also find other uses, such as in education, communicating information, etc. Depending on the purpose of the model, modelers may choose to emphasize physiological detail or statistical efficiency, but generally seek both biological and statistical accuracy.

It is difficult to characterize a generic forest growth model because forests themselves are diverse, ranging from even-aged plantations of a single species to uneven-aged forests with many species. In the latter case, models tend to represent individual trees, whereas in the former case (plantations) other options are available. However, models for plantations of trees tend to be more complex than otherwise comparable models in agriculture and horticulture because "maturity" in a forest plantation may span a period of several years rather than a clearly defined point in time, and because a plantation may be harvested for different products at different points in time (e.g., pulpwood at first thinning, poles at second thinning, sawlogs at final harvest). Because thinning (i.e., an intermediate harvest) and other treatments (e.g., fertilizer, weed control) may substantially influence the subsequent growth of a forest stand (i.e., a homogeneous group of trees), age, by itself, is not a good predictor of tree growth. Thus forest growth models tend to use sets of predictor variables including both site (e.g., some measure of soil fertility) and stand attributes (e.g., measures of tree size, competitive status, and degree of crowding).

A model may be expressed as a yield formulation, $Y_t=f(X)$,

as a difference equation, $\Delta Y=f(Y, X, \Delta t)$

or as a growth relationship, $dY/dt=f'(Y, X)$

where Y is some characteristic at time t, and X is a set of predictor variables. In each case, Y and X may represent tree variables such as age or diameter, or stand variables such as stand density or canopy height. While there are obvious similarities between these alternative formulations, there are substantial differences in the assumptions regarding errors and in the general applicability and utility of the resulting models.

Yield models are most useful in relatively static situations, such as plantations managed under a standard prescription, where the main interest is to predict final yields, notably where the yield table is central to mathematical programming approaches to optimizing management. In more dynamic situations, where management regimes may change over time, or where a larger range of management options may be entertained, growth models offer greater versatility. Since the growth formulation is the first derivative of the yield formulation, many models can be transformed from one form to another (e.g., [5], [7]).

At one extreme, these functions may take the form of a simple relationship such as an equation to predict the final volume of a even-aged single-species industrial plantation from stand age and site index. At another extreme, they may involve a series of relationships to predict the annual height and diameter growth of individual trees of different species in an uneven-aged forest. In either case, it is uncommon that goodness-of-fit statistics offer unequivocal evidence to support the use of one model over alternatives, and the final choice of model may be based on other criteria such as the biological and mathematical implications (e.g., behavior when extrapolated). One notable example is the JABOWA model (e.g, [3], [4]), which contains no relationships based on regression, but relies on ecological understanding, physiological data, and observations on maximum sizes of individual species.

The JABOWA model is concerned primarily with simulating species turnover within a confined area, and size of individuals is of little concern, except to estimate reproductive success. Other models emphasize physiology; some may not discriminate species or plant size, representing vegetation simply as a "green soup", whilst others model crown architecture in considerable detail (see e.g., [8], [11]). In contrast, commercial forestry depends on reliable estimates of stem size (species composition and tree mortality are less important since they are commonly manipulated, e.g., through planting, weed control and thinning), and has motivated much work on developing statistically-based growth models (e.g., [18], [10]).

Many forest growth models rely on a few paradigms of tree and stand growth. At the stand level, models may assume the existence of the self-thinning line ([21], [2]), and that tree volume growth remains near-optimal over wide range of stand density ([20][, [12], [14], [16]). At the individual tree level, models often adopt the Bertalanffy function ([1], [6], [15]) or some generalization ([17[).

The underlying functional relationships form only part of a model. The linkages between relationships, and the way model attributes are represented also affect model performance. Thus for example, models may simulate the growth of the mean (or other representative) tree in a stand and extrapolate to infer population characteristics, they may deal with a list of trees and selected individual attributes, or they may simulate the full spatial development of trees in three dimensions. Such models are often implemented in traditional programming languages such as Fortran or C, but may use specialist languages such as Simile ([13]).

Forest growth and yield models are used routinely in forest management, and increasingly in other applications (e.g., investigation of impacts of climate change), and many users take their reliability for granted. Excellence in predicting yields of large industrial plantations does not infer a general ability to make reliable predictions, yet few models are tested rigorously ([19]). Several challenges remain for model builders. Emerging research includes efficient preparation of error budgets for yield prediction systems, and accommodating spatial and temporal stochastic structure into individual tree growth models ([9]).

References

[1] Bertalanffy, L.v., 1949. Problems of organic growth. *Nature* 163:156-158.

[2] Bi, H., G. Wan and N.D. Turvey, 2000. Estimating the self-thinning boundary line as a density-dependent stochastic biomass frontier. *Ecology* 81:1477-1483.

[3] Botkin, D.B., J.F. Janak and J.R.Wallis, 1972. Some ecological consequences of a computer model of forest growth. *J. Ecol.* 60:849–872.

[4] Botkin, D.B., 1993. *Forest Dynamics: An Ecological Model*. Oxford University Press, NY. (Also see http://www.naturestudy.org/services/jabowa.htm).

[5] Buckman, R.E., 1962. Growth and yield of red pine in MN. USDA For. Serv., Tech. Bull. 1272.

[6] Chapman, D.G., 1961. Statistical problems in dynamics of exploited fisheries populations. In Proc. 4th Berkeley Symp. Math. Stat. and Prob., Univ. Calif. Press, Berkeley, pp.153-168.

[7] Clutter, J.L., 1963. Compatible growth and yield models for loblolly pine. *Forest Science* 9:354–371.

[8] Dixon, R.K., R.S. Meldahl, G.A. Ruark, and W.G. Warren, 1990. *Process Modeling of Forest Growth Responses to Environmental Stress*. Timber Press, Portland.

[9] Fox, J.C., P.K. Ades, H. Bi, 2000. Stochastic structure and individual-tree growth models. *Forest Ecology and Management* 154:261-276.

[10] Gadow, K.v. and G.Y. Hui, 1999. *Modelling forest development*. Kluwer Academic, Dordrecht.

[11] Landsberg, J.J. and S.T. Gower, 1997. *Applications of physiological ecology to forest management*. Academic Press.

[12] Langsæter, A. 1941. Om tynning i enaldret gran- og furuskog. *Meddelelser fra Det norske Skogforsøksvesen* 8: 131-216.

[13] Muetzelfeldt, R.I. and J. Taylor, 1997. The suitability of AME for agroforestry modeling. *Agroforestry Forum* 8(2): 7-9.

[14] Møller, C.M. 1944. Untersuchungen über Laubmenge, Stoffverlust und Stoff-produktion des Waldes. *Det forstlige Forsøgs-væsen i Danmark* 17: 1-287.

[15] Richards, F.J., 1959. A flexible growth function for empirical use. *J. Exp. Bot.* 10:290–300.

[16] Skovsgaard, J.P., 1997. Tyndingsfri Drift af Sitkagran (Management of Sitka Spruce without Thinnings). FSL, Hørsholm.

[17] Vanclay, J.K., 1994. *Modelling Forest Growth and Yield*: Applications to Mixed Tropical Forests. CABI, Wallingford.

[18] Vanclay, J.K., 1995. Growth models for tropical forests: a synthesis of models and methods. *Forest Science* 41:7-42.

[19] Vanclay, J.K. and J.P. Skovsgaard, 1997. Evaluating forest growth models. *Ecological Modelling* 98:1-12.

[20] Wiedemann, E. 1932. *Die Rotbuche*. Schaper; Hannover.

[21] Yoda, K., T. Kira, H. Ogawa and K. Hozumi, 1963. Self-thinning in overcrowded pure stands under cultivated and natural conditions (Intraspecific competition among higher plants XI). *Journal of Biology*, Osaka City University 14:107-129.

Jerome K. Vanclay

From: A. El-Shaarawi and W. Piegorsch (eds) 2002, *Encyclopedia of Environmetrics*, Wiley, NY. ISBN 0-471-89997-6, pp. 811-812.