

Predicting the Yield and Economic Returns of Forest Management in a Changing and Uncertain Future: The Hybrid Simulation Approach

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Abstract. The historical bioassay approach to the prediction of volume and value yields from forest management is probably the best method if future ecological and management conditions are very similar to those of the past rotation. However, under conditions of changing and uncertain future conditions, the predictions of historical bioassay yield models are questionable. The ecological and biological process-based simulation approach to yield and economic prediction is theoretically attractive because of its ability to predict yields in changing futures, but the complexity of this approach has so far restricted it to research and educational applications. However, the combination of these two approaches into a hybrid simulation model (e.g., FORCYTE) appears to offer the best currently available method of predicting long-term forest productivity and yield in a changing and uncertain future.

Introduction

Foresters have traditionally based their predictions of future timber yields and economic returns on their experience of the past. Empirical data on how trees or stands have grown over the past rotation and on the response of trees or stands to various management practices have been combined into various types of "historical bioassay" prediction model. However, such models are only reliable for forecasting future growth and returns on management investments if growth conditions experienced by trees and stands in the future are similar to those of the past.

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The continued growth of the human population and the continuing environmental alteration that is accompanying this growth make it most unlikely that growth conditions will remain the same. More forest products will be demanded from a shrinking area of managed forest. This will require more intensive stand management and biomass utilization, which will result in changes in a variety of soil conditions that have significance for site productivity, and will alter the site/forest growth relationships on which historical bioassay yield predictors are based. In addition to edaphic changes, there is now convincing evidence that anthropogenically induced alterations in atmospheric chemistry are resulting in long-term climatic change (e.g., Bolin et al. 1986; Shands and Hoffman 1987), "acid rain," and air pollution. All three of these atmospheric changes will result in differences in the environmental conditions under which future forest crops will be grown, will alter site/forest growth relationships, and therefore will reduce the accuracy of the predictions of historical bioassay models. Changed climates will probably increase the risk and extent of damage from fire, wind, unseasonable frosts, droughts, and floods. The combination of atmospheric and edaphic changes will undoubtedly alter the biotic interactions between crop trees and non-crop vegetation, animals, and microbes. Hotter, drier climates would exacerbate moisture competition between crop trees and minor vegetation, especially during the early stages of the tree crop rotation, and change the relative competitive abilities of species. The greater stress on trees may alter their susceptibility to pathogens and insect enemies, the abundance and virulence of which may be altered.

Considering the likelihood of these changes, there is a fairly urgent need to develop alternatives to historical bioassay yield prediction models. These alternatives should be able to account for a variety of possible edaphic and climatic change scenarios for which we do not yet have any experience. Because we cannot predict exactly what future forest growth environments will be like, these new models should be considered as "growth trend evaluators" rather than as absolute predictors of future growth and yield. Their role should be to rank the probable yield, economic performance, and various other consequences of various alternative management strategies for various possible future growth conditions.

The objective of this paper is to compare briefly the suitability of two possible approaches to the development of such alternative yield prediction models (process-based simulation models, and hybrid simulation models), and two different approaches to hybrid simulation modelling. Many of the topics discussed in this paper are presented in more detail in Kimmins (1986, 1988) and Kimmins and Sollins (1989, in press). Space restrictions do not permit full references.

Two alternatives to historical bioassay yield simulators

Process-based simulation

The inflexibility of historical bioassay yield models was recognized as early as the mid-nineteenth century by German mensurationists, who concluded that such models should eventually be replaced by models that reflect our understanding of how trees and forests grow (Asmann 1970). This conclusion, which was inspired by the effects of litter-raking on soil fertility and stand productivity in Germany, became one of the motivations behind the development of process-based growth and yield studies, and the whole field of production ecology in forestry.

Process-based physiological, ecophysiological, autecological, population-level, and community-level forest models all have important roles to play in advancing our understanding of the components of forest growth, but they are generally limited in their efficacy as predictors of the structure, net primary production, and economic yield of forest stands over rotation-length periods under a variety of alternative stand management strategies and future environmental conditions. Such models have generally included only a subset of the important growth-determining processes, and this has limited them to retrospective or explanatory roles in those situations in which the action of growth-determinants not simulated by the models is altered. However, as the power of computers and our knowledge of forest ecosystems has improved over the past decade, the number of process-based models that represent forest growth at the ecosystem level has increased.

Hybrid simulation

The difficulty of predicting forest succession on the basis of process-based simulation led Botkin et al. (1972) to develop the JABOWA model. This was probably the first ecosystem-level "hybrid simulation" model of forest growth and stand development, and there is a lineage of subsequent models based thereon. The FORCYTE series of models is another example of this type of model.

The basis for the hybrid simulation approach is the assumption that the best estimate of the rotation-length growth potential of a site for unchanging conditions is the record of growth over the past rotation. This integrates the total effects of all growth determinants on the site over the whole rotation, something that is either extremely difficult or as yet impossible to do in process-based models. The inflexibility of this historical bioassay is overcome by simulating

those growth-determining processes that it is thought will be changed in the types of future that we believe may occur. For changed management intensities, the major changes are expected to be in soil resources and competition between crop and non-crop vegetation. For changed climatic regimes, a greater number of processes must be simulated, but the hybrid simulation approach is still potentially a simpler approach than direct process-based simulation. Hybrid simulation asks the question: "Can the historical pattern of growth reoccur, given the expected changes in growth conditions; and, if not, what growth will occur?" This is an easier modelling task than trying to simulate plant growth and other aspects of ecosystem function solely on the basis of our understanding of the processes that are involved.

JABOWA and FORCYTE lineages of hybrid simulation models

The JABOWA lineage

JABOWA, and the various models developed therefrom, simulates growth of individual trees in a small gap in the forest (e.g., 1/12 ha) by modifying the historical pattern of growth of one or more species (the "historical bioassay") according to the simulated availability of various growth-determining resources or conditions (e.g., light, nutrients, and moisture), or to input data on climatic parameters. These models can simulate mixed-species, mixed-age communities, and the models have proven to be particularly useful for predicting ecological succession in the multi-species eastern deciduous forests of North America and in multi-species tropical forests. However, the JABOWA lineage of models lacks a variety of capabilities that may be necessary for accurate ranking of the long-term growth and yield performance of alternative resource management scenarios.

Changes in site quality as soil nutrient availability changes. The site quality within a climatic region is a multi-dimensional concept that relates to soil fertility (determined by soil processes such as litter decomposition and soil nutrient leaching, and by soil zoology and microbiology) and soil moisture. It has implications for the species composition and productivity of vegetation (overstory and understory), total foliage biomass, the rate of stand self-thinning, plant tissue chemistry, the efficiency of internal cycling, within-plant resource allocation, and several other important parameters. Because plant response to changes in site quality affects both the harvest index (the proportion of net pri-

mary production that is allocated to harvestable biomass) and the response of plants to management-induced changes in soil fertility, hybrid simulation models should include a simulation of site quality change if they are to be used as long-term yield predictors (they should also simulate nutritional regulation of growth if they are to be used for this purpose). Change in site quality also affects competitive relationships between different plant species, and this effect should be represented in succession models, especially if they are to be used to simulate the frequently repeated secondary succession that attends clear cut harvesting of intensively managed forests.

Changes in tissue chemistry and internal cycling as soil nutrient availability changes. As the availability of a soil nutrient declines, plants may reduce the concentration of that nutrient in their tissues, and thereby moderate the growth reduction that may accompany the fertility decline. Similarly, a plant may respond to a decline in soil nutrient availability by internally cycling that nutrient more efficiently at the time of tissue senescence. This strategy can help to sustain growth during short-term fluctuations in soil nutrient availability by maintaining total nutrient availability within the plant, and may prolong the response to fertilization.

Changes in resource allocation to fine roots as soil nutrient availability declines. There is evidence that plants allocate a greater proportion of their growth resources to fine roots as the availability of soil resources declines. Much of the reduction in harvestable yield as site quality declines is believed to be due to this change in resource allocation. Because of the significance of allocation to fine roots for soil organic matter and forest floor accumulation, and because of the importance of this accumulation for long-term soil fertility and site productivity, it is important that any hybrid simulation model that includes nutritional processes should include a simulation of resource allocation and its response to site quality change.

Minor vegetation. Timber yields can be reduced as much by competition or other forms of interference from non-crop vegetation as by declines in soil resources. The classic example of second- and third-rotation yield decline in radiata pine in South Australia (Keeves 1966) is now known to have been the result of the negative influence of minor vegetation as well as the impacts of site preparation methods on soil fertility (Nambiar and Zed 1980; Squire 1983). Non-crop vegetation may limit the response of crop trees to fertilization and thinning, and on many sites "vegetation management" may be one of the most important

management practices in intensive forest management. Hybrid simulation models should have the ability to simulate competition for light, nutrients, and moisture, and possibly other effects such as allelopathy.

Management options. Models that describe long-term succession in unmanaged forest ecosystems are very useful for the development of certain types of resource management policy, as well as for research and education. However, as was concluded by the World Commission on Environment and Development (1987), the majority of the world's productive forest will have to be managed. The response of forests to acid rain, air pollution, and climate change will be influenced by management, and hybrid simulation models should therefore have the capability of simulating the effects of management on ecosystem form and function. Recent modifications to LINKAGES (J. Yarie, unpublished) and to FORET (Waldrop et al. 1986) have provided certain management capabilities to these models, but the list of management options that can be simulated by these models could usefully be expanded. However, a limitation of these models is that they simulate a small gap in a forest, and the deviation of their predictions from reality has been reported to increase as they are used to simulate events in disturbed areas of greater size. Modifications by Smith and Urban (1988) may correct this problem.

The FORCYTE lineage

The FORCYTE model has evolved through a series of stages, but the two major mileposts in this series are FORCYTE-10, and FORCYTE-11. FORCYTE-10 provides the ability to simulate an even-aged, single-species tree crop and associated minor vegetation (shrubs, herbs, and mosses). Nutrient cycling and nutrient limitation of growth are simulated in considerable detail, but competition for water and light are treated very superficially, and there is no representation of the growth of individual trees. A variety of stand-level management activities can be simulated, and the model provides an economic and energy benefit/cost analysis of the simulated tree crop production systems. However, simulation of the effects of variation in stand density is limited, only one limiting nutrient can be represented, there is no ability to investigate the effects of climatic change, and there are several important management activities that cannot be simulated. These limitations largely restrict the use of FORCYTE-10 to educational and research applications. Its value as a management gaming tool is unacceptably limited.

In response to these limitations, FORCYTE was developed to the eleventh version. This is a substantially different model, and as much time was spent on its development as was involved in developing the model up to version 10. The

capabilities of FORCYTE-11 (described in Kimmins 1986, 1988) include all the features noted under the discussion of the JABOWA lineage, but it should be noted that FORCYTE-11 still lacks the ability to simulate competition for moisture and the effects of climatic change. It is planned to add these capabilities in FORCYTE-12, and in a new model, FORCCAST (FOREstry and Climatic Change ASsessmentT), respectively. Major differences between FORCYTE-10 and -11 include the ability of the latter to simulate competition for light, multi-species of any single life form, multiple nutrients, and a much wider range of management practices and natural disturbances.

Surprises revealed during verification of FORCYTE-10

Mechanistic, ecosystem-level computer models have a useful role in education and resource management, but they can also play an important role in research. This role includes the testing of the completeness of the conceptual models on which the computer models are based (i.e., a test of the accuracy of our understanding of the ecosystems being modelled) and of the accuracy of the current wisdom from which the models were developed, and as a means of estimating values for parameters that have not yet been quantified in the field. The use of such models can reveal surprises: future conditions, events or process rates that are different from that which would be predicted by the current wisdom or a non-systems analysis.

Using field data to calibrate FORCYTE-10 for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) in western Oregon, Don Sachs (personal communication) could not simulate a realistic forest floor. Reduction of the decomposition rates in the model resulted in a realistic simulation of forest floor mass, but unrealistically slow tree growth (because of unrealistically low mineralization rates). A re-evaluation of forest floors revealed that much of the mass consisted of rotting wood attributed to periodic catastrophic windthrow or wildfire, occurring about once every 300 to 350 years. When the effect of periodic windthrow was simulated in the model, FORCYTE-10 simulated both tree growth and forest floors reasonably realistically (Sachs and Sollins 1986). Thus, the model revealed an incomplete initial conceptual model, one that ignored long-term episodic events.

Attempts by John Yarie (personal communication) to simulate unmanaged white spruce (*Picea glauca* (Moench) Voss) growth in central Alaska using an early version of FORCYTE-10 were not very successful. The simulated nitrogen cycle tended to stagnate in the forest floor because of low litter mineralization rates. The addition to the model of moss (and its role in N-cycling) corrected the problem (c.f. studies by Tamm, Weetman, Timmer, and Carleton) and resulted

in realistic model behavior (Yarie 1986). Use of FORCYTE-10 in this case confirmed the important role of minor vegetation in the biogeochemistry of forests. The improved model was also used successfully to estimate a soil process rate parameter which had not yet been measured experimentally.

FORCYTE-10 simulates the post-clearcutting flush of nutrients (the "assart" effect), but predictions of nitrate leaching when calibrated for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in coastal British Columbia were much higher than comparable literature values for the west coast (B.C. and the northwestern United States). The problem was investigated in a western hemlock-Pacific silver fir forest by Martin (1985), who identified a post-clearcutting loss of N from the forest floor of about 1,200 kg per hectare over a 3- to 8-year post-cutting period. Measurements of leaching (organic-N, $\text{NH}_4\text{-N}$, and $\text{NO}_3\text{-N}$), and uptake by minor vegetation and regrowth of trees accounted for about 300 kg per hectare. Contrary to the prevailing theory (which was based in part on suction cup lysimeter studies—e.g., Vitousek et al. 1982), Martin presented evidence that both nitrification and denitrification were active in the deep, acidic, freely drained (well-aerated) forest floors on the study sites following clear cutting. In fact, it appeared that denitrification (which was not supposed to occur according to prevailing wisdom at the start of the study) was probably the dominant process of post-logging nitrogen loss from the forest floor. Thus, the model's predictions were wrong because the science upon which the model was based was wrong for the study sites. FORCYTE-10 in fact predicts nitrate disappearance rather than nitrate leaching, and nitrate disappearance on the study sites involved both nitrate leaching and, apparently, denitrification.

Summary

Considering the expected changes in future forest management and climatic conditions, it is unlikely that traditional historical-bioassay approaches to long-term yield prediction in forestry will continue to be considered acceptably accurate. Considering the financial, time, and human resource requirements of calibrating process-based, ecosystem-level models, it is unlikely that such process-based simulation models will provide a practical alternative. The best currently available approach would therefore seem to be the combination of these two approaches in a hybrid simulation model.

At present, there appear to be only two major lineages of this type of model—the JABOWA-derived series of models and the FORCYTE series—although several other models reflect the hybrid simulation philosophy. The two lineages are different. The JABOWA series is designed to assess long-term succession and has the ability to examine the effects of climatic change thereon. The FORCYTE series was designed as a stand management simulator, and its

successional analysis capabilities are limited to secondary succession over the stand cycle and the effects of management thereon. The present version of FORCYTE cannot examine the effects of climatic change, but this capability is planned for a new model, FORCCAST (FOREstry and Climate Change ASsessmentT).

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