Process Models as Tools in Forestry Research and Management

Kurt Johnsen, Lisa Samuelson, Robert Teskey, Steve McNulty, and Tom Fox

ABSTRACT. Forest process models are mathematical representations of biological systems that incorporate our understanding of physiological and ecological mechanisms into predictive algorithms. These models were originally designed and used for research purposes, but are being developed for use in practical forest management. Process models designed for research typically require complicated and intensive data, whereas models designed for management strive to use simpler and more readily available data and provide predictions useful for forest managers. In this article, we review some different types of process models, examine their requirements and utility in research and forest management, and discuss research priority areas that will increase their accuracy and application. We conclude that soil and nutritional limitations are the most difficult model components in predicting growth responses using process models. For. Sci. 47(1):2–8.

Key Words: Scaling, forest complexity, forest modeling approaches, modeling challenges.

Forest process models are mathematical representations of biological systems that incorporate our understanding of physiological and ecological mechanisms into predictive algorithms. Their use in research has developed rapidly in the past 20 yr for two major reasons. First, the steady gain in our understanding of forest biology and ecology has been coupled with great technological improvements in computers and software (Landsberg et al. 1991). Second, and more important, there is a great need to integrate complex layers of biological information. It is clear that some type of modeling is needed to address questions posed at scales higher than those at which processes are being measured (Smith et al. 1998). Integrative modeling exercises have been conducted to refine and interpret complex research activities, to address policy questions, and to develop forest management tools. A wide range of questions are being addressed that include: How will changes in air pollution affect forest health (Luxmoore et al. 1998, Weinstein et al. 1998a,b)? How will climate change affect productivity (McMurtrie and Wang 1993, Valentine et al. 1999)? How can forest management be improved to increase productivity (Sievanen and Burk 1994)? Can we assess the impact of intensive silvicultural practices on the hydrology of forested watersheds (Amatya and Skaggs 2001)?

Modelers attempt to represent mathematically physiological and ecological processes that are affected by changes in resources or stressors and then scale this information up to the level of tree or stand growth. The rationale is that, when integrated, the rates and activities of physiological processes define a tree's (or stand's) growth rate and biomass accumulation. Knowledge at this level introduced into an appropriate model can provide predictive capability, which is a powerful tool for both research and management. Recent progress in process modeling has been extensive and rapid, and modelers

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are now poised to make a substantial impact on both forestry research and management over the next decade. Our objectives in this review are to assess the various types of process models developed for forestry research and forest management and to identify directions for the future development of process models as tools in forestry research and management. Our review is meant to describe the breadth of the field and uses specific examples to demonstrate different approaches; our attention is mostly biased toward models that predict biomass accumulation and allocation. A recent and complimentary review by Mäkelä et al. (2000) describes and evaluates many models not covered here.

Overview of the Basic Challenges and Difficulties of Process Modeling

Tree biomass production is essentially determined by the balance between carbon gained through photosynthesis and that lost through respiration. Tree growth is the product of total biomass production minus losses of ephemeral tissues such as fine roots, foliage, losses in branches (from self-pruning, for instance) and losses due to disease and insects. This residual is incorporated into the structural and storage components of the tree. Absorption of water and essential elements affects carbon balance and alters the allocation of carbon among different tree components. Stand growth is a function of the sum of individual tree growth modified by community dynamics such as competition and mortality.

Although we know a lot about individual physiological processes that control tree growth, developing models that accurately integrate them continues to be a challenge. Tree and forest growth and function is more difficult to model than for food crops, where process-based models are more common and have been successfully incorporated into agronomic practices (Bannayan and Crout 1999). This difficulty stems from both temporal and spatial issues. To represent trees and forests, these models must be accurate over long time periods, under dynamic conditions of weather, changing stages of development, and changing levels of resource availability (Gower et al. 1996). For example, the nitrogen supply capacity of a soil is often high relative to the requirements of a young stand, but this capacity decreases over time as stand biomass increases (as predicted in Dewar and McMurtrie 1996). Nitrogen supply capacity may not be the most limiting factor early in stand development, but is often the dominant limitation at later stages of development. Whitehead et al. (2001), in scaling leaf level physiological parameters to produce estimates of carbon uptake by indigenous forests of New Zealand, determined that annual carbon uptake was highly dependent on N availability of the site. The opposite can be true for water. Seedlings often have a limited rooting system, and they compete with many other species that occupy the same root volume. As trees increase in size, their roots penetrate into deeper soil layers, allowing them to tap into water sources that are unavailable to other plants (Dawson 1996). Furthermore, individual tree hydraulic conductance, the percentage of catabolic versus anabolic tissue, foliage dynamics, and leaf efficiency (production per unit leaf) as well as nutrient dynamics change with stand development (see review by Mencuccini and Grace 1996). These and the many other changes that occur over time, or with resource availability, make accurate modeling of growth and/or growth components problematic.

As processes are scaled up through modeling so are errors due to incomplete or improper model structure, or inaccurate calibration. For instance, a model such as BIOMASS (McMurtrie 1985) simulates carbon gain via photosynthesis and carbon loss via respiration. Net carbon gain is then partitioned among tree organs. The model is typically calibrated from field experimentation. The growth and physiological response curves, root:shoot allometric relationships, phenological data, and so on, that are used to provide calibration of model parameters are, of course, estimated with error. Scaling these model subcomponents over space and time results in error propagation, typically an unknown quantity. Recently, methods have been under development to quantify uncertainty in predictions from process models (Green et al. 2000). And there has been progress in developing methods to validate some predictions from process models (Mäkelä et al 2000, Sievänen et al. 2000).

Overview of Different Modeling Approaches

There is a wide range of approaches that have been taken in the design of models to represent forest growth, from those that greatly simplify the system to those that attempt to fully incorporate its complexity. At one end of this continuum are traditional growth and yield models based on site index that predict future growth based on measurements of historic growth (Short and Burkhart 1996). These models assume site index remains constant, an assumption that greatly simplifies the system. This approach ignores potential changes in environment, genetics, site and silviculture that might occur from rotation to rotation (Bailey and Martin 1996). These models can appear to be too simplistic and unrealistic (Korzukhin et al. 1996) but have provided a high degree of accuracy when averaged across stands in a region (Battaglia and Sands 1998). The historical utility of traditional growth and yield models is because they incorporate mathematical representations of many of the same measurements of growth, such as height and diameter, over the same time period, that they are attempting to predict. Measuring and modeling within the same temporal and spatial scales is an important advantage of this group of predictive models. Their relatively simple data requirements and accuracy in predicting growth have made them the principal yield models of forest management.

At the other end of the continuum are complex process models that incorporate a large amount of information into response functions. For example, in the process models such as BIOMASS (McMurtrie 1985), MAESTRO (Wang and Jarvis 1990), or coupled photosynthesis—stomatal conductance models (Whitehead et al. 2001), carbon gain is initiated at the cellular level using biochemically based photosynthetic models (Farquhar et al. 1980) embedded as subroutines. From that point, the carbon balance of leaves is estimated based on calculated microclimate within the canopy, canopy architecture, leaf area, leaf type (sun, shade), and the resource acquisition of the various portions of the canopy.

These models attempt to represent photosynthesis and many other processes with a high degree of accuracy, which generally translates into a high degree of model complexity. As an example, the need for accurate estimates of leaf photosynthesis and foliage distribution is emphasized by the underestimation of simulated net hourly carbon exchange for slash pine ecosystems in north-central Florida by the process-based model SPM2 (slash pine model II) compared to eddy covariance estimates (Clark et al. 2001). These models, and similar ones such as TREGRO (Weinstein and Yanai 1994) represent the other end of the complexity continuum and are, practically, too complex and data demanding to be of use in forest management applications (Mohren and Burkhart 1996, Korzukhim et al. 1996). However, the photosynthesis-stomatal conductance model described by Whitehead et al. (2001) was found to be useful in calculating a regional estimate of annual C uptake of forests in New Zealand, which is important in understanding the processes regulating ecosystem C budgets. In addition, TREGRO has been linked to the stand level model ZELIG to attempt to scale individual tree responses to the population level (Weinstein et al. 2001).

Between the simple and the very complex models are those that aggregate processes (Smith et al. 1998, Vaisanen et al. 1994). The reasons and types of aggregation are as varied as the models. PnET represents a "stand-alone" aggregate process model. The lumped-parameter (it uses generalized relationships across species) model simulates both carbon and water cycles in a forest ecosystem by using simplified algorithms that describe key processes. Input parameters and driving variables for vegetation, soil, and climate are relatively easy to derive from the literature. Stand level vegetation parameters include foliar nitrogen concentration, maximum photosynthesis, light attenuation, carbon redistribution, and rainfall interception. Only one soil parameter, soil water holding capacity, is required. Climate input data include minimum and maximum air temperature, Photosynthetic Active Radiation (PAR), and total precipitation. Transpiration is directly linked to forest photosynthesis through a constant, water use efficiency. PnET predictions corresponded well to empirical measures in a regional analysis, particularly for transpiration (McNulty et al. 1996). The model has also been tested at two more intensive research sites in North Carolina and performed well on a wet site but poorly on a sandy, dry site (Ge Sun, Research Assistant Professor, North Carolina State University, Raleigh, NC, personal communication). The model has been extrapolated to answer regional questions, such as the effects of climate change (Aber et al. 1995, McNulty et al. 1998), ozone (Ollinger et al. 1997), and nitrogen deposition (Aber et al. 1997) on regional forest productivity.

Another approach attempts to link process and empirical models into "hybrid" models. Mäkelä et al. (2000) proposed that the application of process based models to forest management would be greatly accelerated if both causal and empirical elements were included at the same hierarchical level, an essential quality of hybrid models. In the southeastern United States, this approach has been tried for loblolly pine (*Pinus taeda* L.) by combining PTAEDA and MAESTRO (Baldwin et al. 1998). MAESTRO was used to provide a more accurate estimate of stand carbon gain and allow investigation of potential future environmental scenarios. MAESTRO output became carbon gain input used in PTAEDA, modifying the growth and yield estimates of PTAEDA. In this way, risk assessment, and some additional predictive capability, was introduced into a mensurational model. Baldwin et al. (2001) use the linkage between MAESTRO and PTAEDA2 to predict changes in site index as a function of net photosynthesis, age, and trees per unit area on growth of loblolly pine. Valentine et al. (2000) recently described a model subroutine for initializing a model stand for use in process models. Again, the general application of these approaches is still limited by the disadvantages of process models developed for research, that is, the amount of data and calibration required limits their usefulness to only a few stands where intensive measurements of biology and environmental conditions are available.

Process Models as Research Tools

Process models are valuable, and still underutilized, research tools (e.g., Ceulemans 1996, Dewar et al. 1999). Plant responses to site factors that are manipulated by humans directly, such as fertility, or indirectly, such as atmospheric carbon dioxide concentrations, have their initial effects at the physiological level. For example, the effect of change in atmospheric carbon dioxide concentrations is manifested through the process of photosynthesis, at the scale of individual leaves. In turn, this primary effect changes growth rates, alters investment in growth above and below ground, affects nutrient acquisition and concentrations in tissues, water relations, competitive interactions, rates of decomposition and microbial populations, insect feeding habits, and energy, nutrient, and water flow through the forest ecosystem. Accurately estimating how changes in carbon dioxide concentrations affect the fundamental processes in this chain of events provides the ability to model and predict how a wide range of carbon dioxide concentrations will affect the forest (Cropper et al. 1998, Weinstein et al. 1998b).

From a research standpoint there are many good reasons why process models should be used to an even greater extent than they have to date. One is that we are now attempting to understand the complexity of biological systems, with the realization that responses do not occur in isolation. For example, water uptake and nutrient acquisition are linked activities, yet have rarely been studied simultaneously. Furthermore, process models can provide the tools to overcome temporal and spatial scale-related obstacles in evaluating the productivity of genotypes. Martin et al. (2001) argue that process models can be used to construct genetic ideotypes to improve trait heritabilities and genetic correlations, increase genetic gain in diverse silvicultural environments, guide the development of mating designs, and provide a framework for synthesis of research results from different scales of operation. Process models also provide an excellent means of making research and management more efficient. First, in the development of these models it becomes obvious to the researcher which processes have adequate information for

use in the model and which are relatively unknown. Experiments on the poorly understood processes are more efficient and effective than additional research on well-understood processes. Second, process models can allow generalization across sites if developed properly. Changing nutrient availability could be expected to cause certain responses, which minimizes the need to produce empirical trials for each level of nutrient.

The partitioning of carbon among plant organs has been studied and modeled extensively. In particular, the influence of nutrient and water availability on carbon allocation to foliage versus root greatly affects simulated tree and forest growth rates (Weinstein et al. 2001, Landsberg et al. 2001). Thornley (1997) suggested that all allocation models should be based on the two processes of transport and chemical conversion; he cites numerous examples where his transport-resistance model (Thornley 1971) has been applied/adapted successfully. Pipestem (Valentine et al. 1997) allocates carbon based on pipe-model theory (Shinozaki et al. 1964) and divides dry matter production among foliage, fine-root, woody-root, and woody-stem components to maintain a functional balance (Mäkelä 1986). This approach results in the fraction of available carbon allocated to different tissues varying considerably over the course of the modeled stand development (Valentine et al. 1999). Dean (2001) proposes a novel approach to modeling relative allocation of C to stem and root in response to changes in nutrient or water availability using a constant-stress axiom, that is, the quantity of stem tissue required to counteract increased bending moment controls the availability of carbon for roots.

Process models provide opportunities to explore hypotheses, by providing estimates of the potential magnitude of a response or change. The response of interest can be total growth or a physiological subcomponent of particular interest. For example, because of their important role in internal carbon (C) budgets, labile C pools may provide a measure of the potential ability of trees and stands to respond to stress. Sampson et al. (2001) combined process-based estimates of seasonal net C gain with empirical growth data to estimate labile C pools. The correspondence between modeled and empirical results was only moderate and not of sufficient accuracy to base management decisions on; the bias of the difference provided clues for further research to improve parameterization. However, their results indicated that their approach for assessing labile C pools was reasonable and provides an opportunity for conducting risk analyses for intensive forestry operations.

No person, or group of people, is capable of dealing with all of the complexity of simultaneously changing biological and environmental processes that exist in a forest without the aid of models. The process modeling approach allows researchers to determine the magnitude and trajectory of a response (big or small, increase or decrease) at one or more scales higher than that which was directly observed. Generally, for forests this means tree or stand growth predicted from integrated changes in rates of physiological processes. The integration of processes can be simulated by a model in ways that are impossible to do unaided. This is a powerful tool for considering future conditions and makes process models useful in their present form for applications in both research and forest management. Process models may not, at least initially, be a direct replacement for traditional growth and yield models, but can provide risk assessment of the future forest condition (McMurtrie and Dewar 1997). Given that some future conditions can be projected from our current knowledge of trends, the process modeling approach provides the best opportunity to determine the relative magnitude of response to those changes from the present or past conditions. For example, what will the combined effect of increased nitrogen deposition, elevated atmospheric carbon dioxide and elevated temperatures be on forest productivity? While the specific change in yield will be uncertain, whether these effects will be positive or negative, large or small, can be reasonably ascertained using a process model. Process models have been used to assess the ability of managed forests to sequester carbon (Thornley and Cannell 2000), predict forest growth and species distribution in a changing environment (Kirschbaum 2000), and consider adaptive forest management strategies to cope with climate change (Lindner 2000). Risk assessment of the effects of changing conditions is one of the most important research applications, or extensions, of process models.

Process Models as Forest Management Tools

Forest management occurs at greatly varying scales and intensities. Governments often manage large and diverse landholdings. Ecological considerations and/or societal pressures often demand a large range in forest products. At this largest planning scale, process models are now being evaluated to assist in decision-making. Ditzer et al. (2000) and Bartelink (2000) recently applied a process-based growth model, using a GIS (geographical information system), to conduct a growth and yield analysis to an extended area of tropical rain forest.

At a finer scale, forest managers require information on stand morphological and mensurational details. Bartelink (2000) utilized a mechanistic model to evaluate the impacts of thinning on mixed species stands development. Multiple silvicultural regimes were assessed without expensive and time-consuming field trials. Mäkelä (1997) applied allometric relations, the principle of functional balance and pipe-model theory to derive estimates of the sizes of all functional parts of Scots pine trees. The model was further developed to the within-tree whorl level so that timber quality could be assessed. This approach was then applied to analyses of the impact of different stocking densities on wood quality (Mäkelä et al. 1997).

Intensive fiber and wood production systems are the most likely venue for the development and application of process models in the near future. Even with the inherent difficulties involved in using process level information in management applications (Mohren and Burkhart 1994) and large and distinct differences between the structure of process models and empirical models, there have been attempts to develop process models for management applications (Battaglia and

Sands 1998). There are arguably important reasons for incorporating process information in a greater number of forest management activities, particularly growth and yield predictions, which are the most commonly used models in forestry. One is that the present forest condition is not like that of the past and the future condition is likely to be even more different. For example, intensive management of southern pine plantations, using competition control, fertilization, and superior genotypes can now increase productivity threefold (Borders and Bailey 2000). We appear to be rapidly approaching a time in which growth cannot be reliably predicted from past performance (Bergh et al. 1998, Woodbury et al. 1998). This suggests that the basic premise of empirical growth and yield models, that site index remains constant, is becoming untenable. Temperature and precipitation patterns have been changing. Carbon dioxide concentrations in the air, and nitrogen and sulfur deposition to the soil have been steadily increasing. Genetics, fertilization, competition and insect control, planting practices, and virtually every other silvicultural practice has undergone changes that affect the site growth potential. We cannot wait for another forest to grow to harvest age to provide the answers we need. The results will only reflect the past, not the future. Ung et al. (2001) demonstrated that it is possible to derive site indices for growth and yield models from biophysical variables, such as climate and soil, which allows more consistent prediction of site potential under diverse conditions and interfacing with geographic information systems.

An example of the use of process models to develop site-specific fertilizer prescriptions is given by Ducey and Allen (2001), who simulated the 10-yr macronutrient budget and fertilizer efficiency for N and P for midrotation loblolly pine using NUTREM, a model of C and nutrient uptake and distribution. In this case the efficiency provided by a process model is in saving both time and money. From a practical standpoint, the expense of field trials may ultimately be one of the most important reasons for incorporating process information into management models.

The desire to have more process information in mensurational applications has spurred the development of more generalized and simplified process models (Amateis 1994, Landsberg and Waring 1997, Sands et al. 2000). This type of model is designed specifically to bridge the gap between what are conventional process models and conventional growth and yield models. By necessity this type of model represents biological processes as aggregates of many processes. Key features of this model type are that they are designed to be transportable across many forests and site conditions, in large part by restricting their data requirements to information that can be readily obtained, such as monthly weather data, aggregating processes into indices and using parameters that are normally measured in forest inventory activities and/or estimated using remote sensing (Coops et al. 1998).

Sands et al. (2000) have developed PROMOD, a simple plantation productivity model intended for screening potential plantation sites. PROMOD uses readily available input data including site latitude, soil characteristics and long-term climate data. The model developers have maintained strong links with actual and potential users, which kept the model on track as a true management tool. The model is a hybrid in the sense that it uses established physiological principals but also relies on empirical relationships, for instance in portioning biomass among tree parts. This approach requires the model to be parameterized for different species and regions, but the results are applicable for on-the-ground management decisions.

The model 3-PG (Landsberg and Waring 1997) was developed with the intent of being both simple and applicable to management. 3-PG is a hybrid model based on physiological principles and parameterized with empirical data. It uses the concept of radiation use efficiency where potential carbon gain is then constrained by the biology of the species and the physical characteristics of the site. An important feature of the model is that the output variables it produces are those of interest and utility to forest managers. Landsberg et al. (2001) demonstrate the potential of this approach using loblolly pine.

Although 3-PG (Landsberg et al. 2001), when parameterized from an intensive research site, very accurately predicted growth on an adjacent plantation, its fertility rating (FR), a major control of predicted productivity, was empirical and crude. The evolution of BIOMASS (McMurtrie 1985) into the model G'DAY (Comins and McMurtrie 1993) resulted in incorporating soil processes and feedbacks; our ability to do this successfully across a large range of sites may be the biggest challenge in process modeling. Better understanding of the interaction between foliage production and foliage nutrient dynamics in response to site fertility and soil nutrient availability (Landsberg et al. 2001) would improve the development of process models as tools in forest research and management.

Conclusions

Forests are, obviously, very complex ecosystems; the degree to which process models attempt to mimic this complexity largely dictates their use for research and/or management. There has been a general trend in forest growth models, process models, and ecological models toward more complexity (Peters 1993), although there are some notable exceptions (Comins and McMurtrie 1993, Landsberg and Waring 1997). In process models of forest growth, an increase in resolution is often accompanied by an increase in complexity (Battaglia and Sands 1998). Accuracy can be improved when more functions and parameters are included, but increased complexity reduces the generality and broad utility of a process model.

A model designed for a specific purpose usually cannot be used for other purposes without introducing inefficiencies and errors. For example, process models designed for research or risk assessment applications cannot be easily made to provide useful information for specific management objectives. Models designed for management can certainly utilize concepts from research models but must avoid the complication of research models. Research models, however, can be useful for calibrating simpler "top-down" models as recently demonstrated by Raulier et al. (2000).

Based on our review of process models in forestry, we conclude that soil and nutritional limitations are the most difficult model component to make transportable among sites and species, and thus model-guided research on soil and plant nutrient dynamics is needed to increase the application of process models in forest management. The ability of process or hybrid models to eventually usurp site index-based empirical models as the primary forest management tool will require that relatively simple and standard indices of nutritional limitations be developed.

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