COMMENTARY / COMMENTAIRE

Modelling forest ecosystems: state of the art, challenges, and future directions

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Abstract: Forest models should in future combine the predictive power and flexibility of process-based models with the empirical information and descriptive accuracy of conventional mensuration-based models. Progress is likely to be rapid if model developers identify the potential users of their models and the needs of those users. Users include operational forest managers, planners, bureaucrats, politicians, community and environmental groups, scientists, and academics. Extant models that could be used immediately or could be adapted for use by these groups are reviewed. Currently available process-based models can provide good estimates of growth and biomass productivity at various scales; combined with conventional models they can provide information of the type required by managers and planners. Climate-driven models can provide good estimates of potential plantation productivity, while detailed process models contribute to our understanding of the way systems function and are essential for future progress. Technical challenges for the future include continued research on carbon-allocation processes, nutrient availability in soils, and nutrient uptake by trees. It is important that we have models that can be used to predict and analyze the effects of technologies such as clonal forestry and possible genetic manipulation, as well as intensive management in relation to nutrition, weed control, and disease control. Large-scale analysis of forest productivity is already possible using models driven by remote sensing; inclusion of nutrition should be a goal in this area. Moves towards active collaboration and the implementation of mixed models in operational systems, as well as improving communication between model developers and users, should ensure that practical problems are identified and fed back to modellers, which should lead to rapid progress.

Résumé : Les modèles de forêt devraient combiner dans le futur la puissance prédictive et la flexibilité des modèles basés sur les processus, avec l'information empirique et la précision descriptive des modèles conventionnels basés sur les mesures. Le progrès sera sans doute rapide si les développeurs de modèles identifient les utilisateurs potentiels de leurs modèles ainsi que leurs besoins. Parmi ces utilisateurs, il y a les aménagistes forestiers, les planificateurs, les bureaucrates, les politiciens, les groupes communautaires et environnementaux, les scientifiques et les académiciens. Les modèles existants qui pourraient être utilisés immédiatement ou être adaptés à l'usage de ces groupes sont passés en revue. Les modèles basés sur les processus qui sont couramment disponibles peuvent fournir de bons estimés de la croissance et de la productivité en biomasse à plusieurs échelles; combinés avec les modèles conventionnels, ils peuvent fournir l'information du type requis par les aménagistes et les planificateurs. Les modèles basés sur le climat peuvent fournir de bons estimés de la productivité potentielle des plantations, alors que les modèles détaillés de processus contribuent à notre compréhension du fonctionnement des systèmes et sont essentiels au progrès futur. La poursuite de la recherche sur les processus d'allocation du carbone, la disponibilité des nutriments dans les sols et le prélèvement des nutriments par les arbres fait partie des défis techniques pour le futur. Il est important que nous disposions de modèles qui puissent être utilisés pour prédire et analyser les effets des technologies telles que la foresterie clonale et les manipulations génétiques potentielles, de même que l'aménagement intensif en relation avec la nutrition et le contrôle des mauvaises herbes et des maladies. Une analyse à grande échelle de la productivité forestière est déjà possible en utilisant des modèles basés sur la télédétection; l'inclusion de la nutrition devrait être un but dans ce domaine. Une incitation à une collaboration active et l'application de modèles mixtes dans des systèmes opérationnels de même que l'amélioration de la communication entre les développeurs de modèles et leurs utilisateurs devraient garantir que les problèmes pratiques sont identifiés et alimentent en retour les modélisateurs, ce qui devrait engendrer un progrès rapide.

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Introduction

The objective of the conference to which this paper was a contribution was to discuss how current and future modelling efforts will address the information needs for ecosystem management, forest certification, and sustainable manage-

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ment. I will not address the question of certification, since I am not familiar with the procedure, but will try to evaluate how much of the information required by those responsible for, or concerned with, the management of forests can be provided by the current generation of models. On that basis I will try to identify the challenges faced by forest modellers and the most useful future directions for their work.

The information needed by forest managers depends on whether forests are being managed primarily as wood-production systems or for other forest values and whether the managers are closely involved with operational decisions or more concerned with policy and longer term considerations, which will inevitably involve consideration of the sustainability of various options. Therefore, to identify the information needs of forest managers, and the challenges and future directions for forest models, we have to consider who the managers are and what they are trying to achieve.

Forest managers concerned primarily with wood production will require information on the present status of the resource (e.g., number of trees by species and sizes, etc.), forecasts of the nature and timing of future harvests, and estimates of the maximum sustainable harvest (Vanclay 1994). Managers, or others, concerned with nonwood values may require different information. In either case they are likely to use some sort of model to provide the information needed.

Models of any sort are abstractions that should encapsulate the essential features of the system being modelled, although they can very seldom provide unequivocal answers; there is always experience and judgement involved in their use. Conventional, empirical, growth and yield models are developed from (usually) large amounts of field data to meet the needs of managers. Vanclay (1994) commented on the need for a stronger mechanistic basis for the functional relationships used in such models. Progress in making accurate predictions about forest conditions and responses to future environmental conditions and management actions will be more rapid if, wherever possible, we combine conventional and process-based models. Conventional models provide statistical descriptive accuracy; process-based models potentially provide greater flexibility, generality, and predictive power. The term "process model" implies a model of a particular process, e.g., leaf photosynthesis, carbohydrate allocation, plant water status, and stomatal responses. A process-based model implies a model of a system and its behaviour, at whatever level of complexity, based on the (sub-)models of the constituent processes that together determine the behaviour and responses of the system (see Landsberg 1986). The term process-based model, abbreviated to PBM, will be used throughout this paper.

Mäkelä and Hari (1986) appear to have been among the first to recognize the need to develop process-based growth and yield models simultaneously with the more traditional statistical ones. They described a stand growth model in which biomass production was determined by physiological processes, but the time course of tree growth was based on tree geometry and an empirical competition index. Korzukhin et al. (1996) reviewed the question of process-based or mechanistic, as opposed to empirical, models. They concluded that process models offer significant advantages over empirical models for increasing our understanding of, and predicting, forest behaviour and are, therefore, more likely to meet the information challenges presented by ecosystem management. Mäkelä et al. (2000) argued that the future lies in mixed or hybrid models that combine biophysical processes and relationships based on tree- or stand-level measurements. They noted that if decision-making and analysis in forest management are to move towards a more general causal-oriented approach, mutual appreciation of methods and approaches by ecophysiological and empirical modellers, and a close interaction between modellers and forestry practitioners, is essential. Battaglia and Sands (1998), in their review of the application of PBMs to forest management, made the same point and asserted that the process of determining an appropriate model structure must start with the end user, whose needs determine the model context, the questions to be addressed, the accuracy required of estimates, and the range of situations or environments over which the model is to be applied. This was restated more strongly by Sands et al. (2000), who argued that PBMs have a potentially valuable role in forest management, but the fulfillment of this potential will be greatly enhanced if the developers of a model involve prospective clients in model development and work closely with them in developing applications.

I endorse the views outlined above. The following section provides an outline of the clients or end users for forest models and the (assumed) management objectives of those clients: why do we expect that they will (should?) use forest models as management tools, and what sort of information are they likely to want from those models? The section, "Characteristics of currently available process-based and hybrid models", deals with the state-of-the-art PBMs; the characteristics considered potentially relevant to the management problems of the different client groups are reviewed, and their properties discussed. The last part of the paper outlines the challenges, scientific and operational, that we face to increase the relevance and application of the models concerned with sustainable wood production and provides some ideas about future directions.

Model users and their needs

Any division into categories of the groups who use, or could use, forestry models is inevitably arbitrary; the groups merge and overlap, and individuals and organizations may fall into one or another category at different times and in relation to different problems. However, the division serves a purpose in focussing attention on the fact that requirements for information about forests and the consequences of disturbing them vary widely; "forest managers" are not a homogeneous group, and there is no universal model that can provide for all user needs.

Model users can be grouped into forest industries, the broader public community, and the academic and scientific communities. Forest industries are taken to include individuals and organizations concerned with managing forests as wood-production systems; the broader public community may include community groups as well as bureaucrats and politicians in organizations such as regional and local governments; and the academic and scientific communities largely consist of people in universities and research institutions. All these groups may use models as tools to aid decision-making, although this does not imply that the analysis, or simulation results, will necessarily be used directly. In many cases the models will be used as guides and as means of exploring options and alternatives, of evaluating the consequences of particular actions, or of examining the sensitivity of the system to specified disturbance or lack of it. If models are used, for example, as a basis for economic analysis, then clearly their outputs need to be quantitatively reliable, but this is not always necessary. Relative and qualitative results can be immensely valuable.

Forest industries

Forest industries may be represented by state organizations or by private companies who own or lease tracts of forested land. They will vary between countries. Depending on the structure and hierarchy of the organization the operational forest manager (the manager “on the ground”) will be concerned with operations such as determining and overseeing logging schedules, thinning, re-establishment, thinning, and disease and weed control. Managers at this level will know their forest well and may make operational decisions about management on their own responsibility, consistent with company or agency policy and plans. They may be responsible for the activities of mensuration teams but will almost certainly not be responsible for analysis of data and model development. Vanclay (1994) specified an important requirement for model implementation and use, relevant to any model, that applies particularly to operational managers: the (growth) model should be viewed as a tool to provide better information for forest management but must not threaten the experience and judgement of the manager.

If operational managers are to use process-based models they will require a software package that is simple to operate and requires few parameter values. These should be obtainable from easily accessible information (e.g., stand age and stocking, soil maps, and weather files). It is difficult to imagine that managers at this level will have any interest in multiparameter models that are opaque to them.

At higher levels in the organization, managers and planners will deal with larger scale questions such as wood flow and market requirements or the economics of alternative management practices, such as thinning or fertilization. If the enterprise is based wholly or primarily on short-rotation plantations, which may be significantly affected by poor weather during a single year, they may be concerned to estimate the effects of adverse seasons on productivity or the effects of defoliating diseases or insect attack. For all these purposes they need models that can account for environmental conditions and be used to explore alternative scenarios. Commercial companies also need to know the probable productivity of new land to make decisions about purchase and development.

Plantations, primarily for pulpwood, are expanding rapidly in a number of countries (e.g., Australia, Brazil, Portugal, South Africa, China, etc.). Large areas in these (and other countries) are being planted to *Eucalyptus*. In the United States the areas being planted to pine (particularly loblolly pine, *Pinus taeda* L.) are increasing rapidly in the southern parts of the country as the forestry industries seek to develop new resources to replace the increasing areas of natural forest closed to logging. The technology (e.g., clonal forestry) and silvicultural practices (e.g., intensive fertilization, weed and insect control) being used in these plantations are, in many cases, new and the rate of change is outstripping the capacity to gather mensuration data. Mensuration data are essential, but process-based models that can simulate the growth patterns of these trees in terms of the biophysical mechanisms that determine their growth and responses to manipulation are also essential.

The broader public community

There is considerable concern in the broader public community, in many countries, about the use and sustainability of natural forests. Negotiations relating to the exclusion of areas of natural forests from commercial exploitation will involve considerations of the potential wood yield of forests and the economic value of that yield, including jobs and the people that the industry supports, as opposed to considerations such as the value of forests as water yielding catchments and unquantifiable values such as wildlife and biodiversity. Assessment of potential yield in any given area essentially involves estimation of total aboveground biomass production; estimates of the economic value of that biomass involves prediction of stem size distribution and wood quality. The estimates need not be accurate for any particular site, but they need to reflect the probable overall value of the forest production in the area of interest. An example from Australia indicates the need for models that can provide accurate estimates of the productivity of natural forests and the potential productivity of plantations as alternative sources of wood in areas where they have not yet been grown.

The original mandate of the Australian State forest services was to ensure wood supplies to the community, which entailed, primarily, utilization of the apparently abundant natural (hardwood) forests. (South Australia, with virtually no natural forests, established a plantation-based softwood industry more than 100 years ago.) In other States, there is still a great deal of logging in natural forests, but public pressure to reduce this, and focus the wood-producing industries on plantations, has been increasing steadily in recent years. Consequently, State forest services have been heavily involved in negotiations between the Federal government and the forest industries in general, concerning the reduction of logging in natural forests. The regional forest agreements (RFAs) are agreements between the Commonwealth and State governments that aim to provide a comprehensive, adequate, and representative forest reserve system. They are also intended to safeguard local forest industries and regional communities and enable the development of internationally competitive and ecologically sustainable industries. Management of the whole forest estate, both on and off reserves, should be ecologically sustainable.

The State forest services, like the forestry companies licensed to log natural forests, historically estimated the wood yield of those forests using empirical models based on measurements. However, the RFAs required estimates of the wood production potential of large areas of forest that had never been measured so that comparisons could be made with (potential) production from the plantations, as yet unplanted, that will have to provide the wood needed if forestry industries are to survive in those areas. Process-based models were used in some of these negotiations, but in general, because of time constraints, the productivity estimates used owed more to experience, guesswork and "rule of thumb" than science. Hopefully, as the agreements are reviewed and refined, this will be rectified.

At the national and international level the question of carbon sequestration by forests is becoming of increasing importance in relation to climate change and its consequences. This includes questions such as long-term sustainability, not only in terms of wood yield but also of nutrient immobilization in soil organic matter and the carbon sink strength of forest ecosystems over relatively long periods into the future. At the international level the International Panel on Climate Change (Web site: www.ipc.ch) reports, heavily dependent on modelling, have been crucial factors in raising political awareness and concern about climate change and its implications.

In developed countries, the community groups concerned with forestry may include the populations of rural towns where the economic base is threatened by logging bans, and (or) environmental groups concerned with the impact of logging on natural forests, or the advance of plantations into areas previously covered by natural forests. These groups will take opposing points of view. The data base available from natural forests to address questions of this type is, in many cases, very poor and inadequate to unequivocally support one argument or the other; the use of appropriate, science-based, and reliable models can be a very important tool in helping these discussions and arguments reach a rational conclusion. The type of model needed may range from wide-scale estimation of net primary production in natural forests, using geographical information systems (GIS) based on satellite measurements and what survey data are available, to models for the growth of even-aged monospecific plantations, which can be used to provide estimates of the potential return on those plantations, their rotation time, and other matters relating to their introduction in new areas (see Sands et al. 2000). It may be possible to evaluate some of the concerns about matters such as the effects of clear-cutting on biodiversity using models of the succession type (see later).

In underdeveloped countries the primary concern of many communities is for wood supplies. This requirement can frequently be met by plantations. Aid donors and aid administration organizations would, in many cases, be well advised to use models that can provide reasonable estimates of the probable productivity of plantations in particular areas. It is also worth considering the question of water use and the possible effects of plantations on the water balance of an area; large areas of deep-rooted evergreen trees can cause sufficient disruption to the local hydrology to reduce stream flows, with severe detrimental effects on local water supplies. Like arguments about logging natural forests in developed countries, the judgement about the relative values of wood and water will always be subjective, but the use of good-quality models for calculating wood production, which also provide estimates of water use, will always be valuable in helping to guide discussion and explore the implications of various alternatives.

The academic and scientific communities

Although I have no data on the matter, it seems safe to assume that most process-based modelling is done by scientists who are either in universities or in institutions such as government research organizations. There is an entirely legitimate role for this kind of work in universities; the target audience is, in most cases, other academics and scientists. The objective of the modelling exercises is to improve understanding of the processes and the factors affecting forest growth. There is also a strong motivation to make progress that leads to professional recognition and furthers career development. The development of models of any type in the academic community also contributes to the ability of the people concerned to teach effectively.

Scientists in universities may undertake contract work to develop models needed to meet the requirements of politicians, bureaucrats, or industry, but in most cases, models developed in the academic community are not intended as practical management tools. They provide a vital source of understanding and techniques that, directly and indirectly, contribute to the modelling exercises carried out by people more concerned with management. Scientists in government agencies and research institutions are in a slightly different situation from those in universities. Their objective is to produce models or information that will be available to managers in industry or relevant to bureaucratic or political decision-making, but in many (perhaps most) cases the models developed in these organizations are oriented more towards the academic–scientific community than towards particular clients or management activities. The problem is very often one of communication: politicians tend to work with relatively short time horizons; answers are needed now ("the minister requires a briefing…"!), which are reflected in the time horizons to which bureaucrats must work, so the scientists have to try to anticipate the problems. Therefore, much of the time they are working on problems perceived as relevant by the scientific community (which they hope will be relevant to the bureaucrats and politicians) rather than on problems identified as relevant by their primary customers.

Characteristics of some currently available process-based and hybrid models

The models considered in this section are categorized as relating to the user groups identified in the previous section, although in most cases, they may not have been written with those (or any other specific) groups in mind. However, the models in each group have characteristics that would allow them, often with some modification or additional work, to meet the (probable) requirements and objectives of clients in that group. The selection considered is not exhaustive, and the models are not critically reviewed at this point.

Models relating to industry

All the models in this group are essentially carbon balance models, combined with some means of allocating carbon to stems to produce results useful to forest managers. The "target clients" are managers at either the operational or planning levels.

The "pathfinding" models of this type were written by Mohren et al. (1984) and by Mäkelä and Hari (1986). Both are essentially hybrid models. Mohren et al. described stand growth in terms of simplified physiological processes and assimilate distribution leading to the calculation of potential productivity; actual productivity was estimated on the basis of site factors and current yield tables for even-aged stands of *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir). The model worked with average weather data on a yearly time step and did not include the dynamics of water relations and nutrient supply. It included the number of trees per hectare (stocking) and shading as the basis of crown projections. A major feature was the thinning routine. Stand structure was represented by equations very similar to those used in conventional modelling. The Mäkelä and Hari model, written for *Pinus sylvestris* L. (Scots pine), shared many of those features but was aimed more at simulating stand growth and competition between individual trees, focussing on needle biomass and crown closure. Mohren et al. parameterized their model for a number of permanent field plots and simulated the time course of stem volume development in those plots. The simulations corresponded satisfactorily to field measurements. They did not attempt to modify the model to improve the fit. Mäkelä and Hari simulated the time course of stem height, stand volume, and population density for two site types. They also obtained satisfactory results but did not attempt to improve on these.

Kimmins et al. (1990) was among those who recognized early the need for PBMs and hybrid simulation yield predictors. Kimmins and coworkers (see references in Kimmins et al. 1990) developed the FORCYTE model with support from, and in collaboration with, the Canadian Forest Service, so this was certainly a model intended to be of value to forest managers. However, since it is a comprehensive forest ecosystem model intended to predict the consequences of actions such as forest harvesting and fire, it would also fit comfortably into the category of models relating to the broader public community. FORCYTE-11 (described in detail by Kimmins et al. 1999) aims to simulate the light climate and the availability and dynamics of up to five nutrients and their effects on tree growth and secondary succession over the management cycle, as well as interactions between herbs, shrubs, and trees. The model is immensely complicated and undoubtedly represents an excellent summary of current knowledge about (temperate) forest ecosystems; it also purports to deal in detail with the question of nutrient availability and site quality. FORCYTE requires a considerable amount of input information, and the complexity of the model makes it difficult to envisage how it could be rigourously tested in any quantitative sense. Some of the input information (e.g., root biomass, N-fixation rates in litter types, etc.) will always be highly uncertain, and FORCYTE includes so many processes and submodels that it would be difficult to assess the impact of the many assumptions and estimates and the functional forms used for the submodels. Most of the work evaluating the performance of the model is published in conference proceedings and seminars; there does not appear to be an account, in the open literature, of testing and evaluation of the model's performance against observed data. Determining parameter values (their range and generality) for this type of model and studying the effects of parameter variation on submodel interactions and outputs is currently an area of science that requires considerable attention.

Sievänen (1993) produced a model of the dimensional growth of even-aged stands in which biomass production was calculated from intercepted radiation and a canopy conversion efficiency (ε, biomass produced per unit intercepted light[1]). Respiration and senescence terms gave the carbon balance. The coefficients for the respiration equations, the carbon partitioning equations, and hence the complete growth patterns of the trees, were obtained in terms of empirical allometric equations for stem diameter, height, and the height of the crown base. Sievänen and Burk (1993) provided the statistical methods needed to estimate the parameters of the Sievänen model from plot data for *Pinus resinosa* Ait. (red pine) in the Lake States region of the United States. Mäkelä (1997) used an analogous approach but invoked the pipe-model theory (Shinozaki et al. 1964), which implies that the sapwood area and foliage mass above a given height are related in a constant ratio. She used this idea, and allometric relations including height to crown base, to produce a model of growth and self-pruning in trees, again parameterized for Scots pine. The model could be used for the assessment of timber quality.

3-PG (Landsberg and Waring 1997) is a generalized stand model (i.e., it is not site or species specific but needs to be parameterized for individual species) applicable to plantations or even-aged, relatively homogeneous forests that was developed in a deliberate attempt to bridge the gap between conventional, mensuration-based growth and yield and process-based carbon-balance models. The model consists, essentially, of two sets of calculations: those that lead to biomass values and those that distribute biomass between various parts of the trees and, hence, determine the growth pattern of the stand. It includes water use and soil water balance calculations. Time step is a month, and the state of the stand is updated each month. 3-PG is driven by radiation; conversion efficiency is modified by temperature, atmospheric vapour pressure deficit, soil water balance, and nutrition, represented by a soil fertility rating. Net primary production (NPP) is assumed to be a constant fraction of gross primary production (GPP). Carbon allocation to stems and foliage is on a single-tree basis and relies on the ratio of the derivatives of the allometric equations describing leaf and stem mass in terms of stem diameter at 1.3 m above the ground. The model includes a mortality function. Output variables include monthly or annual values of leaf area index (L^*), stem mass and volume, stem growth rate, mean annual (volume) increment (MAI), stem basal area, and stem number. Litterfall (mass) and root turnover are calculated from input rates. Stand transpiration and evaporation of intercepted water are calculated, producing monthly soil water balance values.

3-PG has been evaluated as a stand growth model in Australia (Coops et al. 1998*a*; Sands and Landsberg 2001), New Zealand (Coops et al. 1998*b*), in the United Kingdom (Waring 2000), the southeastern United States (Landsberg et al. 2000), and in Brazil (Almeida et al. 2003*a*). Tickle et al. (2001*a*, 2001*b*) used it to make spatially explicit predictions of growth and yield over 50 000 ha of natural forest in New South Wales. The predictions were compared with estimates made from growth measurements in 22 plots using conventional empirical models. Tickle et al. (2001*a*) also used 3-PG to estimate "site index" for homogeneous polygons

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[1] ε is not the symbol used by Sievänen, but it occurs in a number of cases and will be used for all the models discussed.

(weighted for soil type and topography) across the whole area; when these estimates were used with a conventional model, the results were within 1% of results obtained using the process-based model alone. 3-PG appears to be the first model of this type that has been adopted as an operational tool by a commercial forestry company (see Challenges and the future section).

FOREST-BGC (Running and Coughlan 1988; Running and Gower 1991) is probably the best known process-based model of forest growth. It includes hydrologic, photosynthetic, and maintenance respiration processes computed daily and carbon allocation and nitrogen processes computed annually. FOREST-BGC was originally formulated, and has been widely used, with outputs in terms of biomass pools ($t \cdot ha^{-1} \cdot year^{-1}$), which are of little interest to forest managers. However, Korol et al. (1996) have used it in hybrid form, using relationships between stand volume, height, and stem diameter derived from measurements on 352 Douglas-fir trees in 24 uneven-aged plots in British Columbia. Daily climate data were obtained from local sites and the MT-CLIM climate simulation package (Running et al. 1987; see Thornton et al. 1997 for recent developments). The model allocated carbon to individual trees on the basis of their relative sizes and allometric relationships. Korol et al. note that they obtained reasonable estimates of NPP available for growth and a high correlation between measured and modelled stand volume increment and basal area increment. FOREST-BGC was also used by Milner et al. (1996) to predict potential forest productivity for the state of Montana. They used MT-CLIM and then regression of potential productivity estimates against site index values for plots where those were available. They concluded that the results of this work illustrate an application of existing technology that should prove useful in land use planning.

Battaglia and Sands (1997) produced a model (PROMOD) to estimate site productivity, in terms of mean annual increment (MAI) of *Eucalyptus globulus* Labill. plantations in Tasmania. PROMOD contains simple empirical relationships for closed-canopy leaf area index in terms of site climate factors. Soils information includes water-holding capacity and a fertility index. It includes a canopy photosynthesis production model and respiration calculations, a standard water balance model and carbon allocation to stems and foliage on the basis of empirical relationships. Sands et al. (2000) subsequently parameterized PROMOD for *Eucalyptus nitens* Dean & Maid. and *Pinus radiata* D. Don. PROMOD has been used for predicting responses to irrigation, for producing broad-area maps of site productivity across Tasmania, and, by combining it with a conventional empirical growth model, for predicting stand development.

Models relating to the broader public community

Concerns about climate change, the impact of commercial forestry activities, particularly clear-cutting, land development, and the impact of diseases all lead to questions about the capacity of mixed-species forests to regenerate over long periods and the composition of the regenerating forests.

The succession or gap models that derived from the work of Botkin et al. (1972; see also Botkin 1993) were developed for regional-scale analysis of forest dynamics (see Shugart 1984). In general, they simulate establishment as a stochastic process constrained by environmental filters. The growth of trees is simulated in terms of species-specific empirical relationships describing height and diameter growth, constrained by temperature, drought, and nitrogen dynamics formulated in various ways. Competition is simulated by shading based on height and canopy size relationships. There have been various additions to these models that have become very complex. Bugmann et al. (1996) reviewed the performance of a number of them and concluded that the behaviour of forest gap models is quite sensitive to the precise formulation of the ecological factors included in them. Bugmann (1996) went on to test the use of six plant functional types (PFTs), rather than a large number of species-specific parameters in his (relatively simple) FORCLIM gap model. He found that the implementation of the PFT concept led to simulation results that paralleled the species-based approach closely. The fact that 39 tree species in Europe and 72 species in eastern north America could be replaced by the same set of six PFTs also holds promise for the applicability of forest gap models over large areas.

Ditzer et al. (2000) applied a model called Formix 3-Q to the estimation of timber yields and the sustainability of logging in 55 000 ha of tropical mixed forest in Malaysia. The model included procedures analogous to those common in succession models. The growth of trees was described by form factors and allometric relationships, with dry mass production estimated from light interception and a standard value of ε. Respiration is estimated by manipulation of the allometric equations to give trees size increments. The model includes shading to account for competition between individuals. Ditzer et al. characterized the forest in terms of the characteristics of groups of tree species. Site quality was estimated from soil maps giving nutrient concentrations and plant available water. Using stratification procedures and GIS, the authors simulated successional development, aboveground biomass, and the impacts of logging. The results could not be tested but illustrated how such a model can provide information that would otherwise be very difficult to obtain and can contribute to management decisions.

3-PG, FOREST-BGC, and PROMOD can all (potentially) be applied to problems relevant to those concerned with wide-scale land-use planning and issues such as the potential productivity of forest plantations in particular areas, relative to other land uses. Both FOREST-BGC and 3-PG can be driven by satellite data, from which estimates of L^* of forest stands can be obtained; these, combined with climate data, allow the model to be used to simulate forest growth over large areas (see Running et al. 1988; Coops et al. 1998*a*, 1998*b*; Coops 1999; Coops and Waring 2001*a*, 2001*b*). All these models can also provide estimates of carbon sequestration by forests.

Comins and McMurtrie (1993) produced a model (generic decomposition and yield; G'DAY) that describes how photosynthesis and nutritional factors interact to determine the productivity of forests growing under N-limited conditions. G'DAY is intended to provide qualitative understanding of the flows of carbon and nutrients into and out of the pools (component parts of the stand). It is mathematically elegant and is generally run to equilibrium to evaluate the consequences of various assumptions about utilization and supply rates. A modified version of the widely used CENTURY model (Parton et al. 1988) is used to estimate N-mineralization rates from (assumed) soil organic matter composition, and the C:N ratios of plant and soil pools are specified. The original analysis provides insights into the probable interactions between increased photosynthetic rates that might result from increased atmospheric CO_2 concentrations with nitrogen supply constraints and the likely equilibrium situations. Later work with G'DAY includes further analysis of climate-change scenarios (e.g., Kirschbaum et al. 1994; Mooney et al. 1999), as well as various other theoretical analyses. Murty et al. (1996) used it to explore the reasons for the widely observed age related decline in stand productivity by incorporating (*i*) specific assumptions about respiration; (*ii*) assumptions about the effects of age on stomatal conductance and, hence, canopy photosynthetic efficiency; and (*iii*) variable soil C:N ratios. The analysis yielded information about the consequences of the various hypotheses and the circumstances under which they might explain productivity decline. Dewar and McMurtrie (1996*a*, 1996*b*) used G'DAY to examine the effects of climate and nutrient supply on sustainable forest productivity (in terms of stemwood growth), examining the implications of alternative assumptions, and on sustainable yield in relation to nitrogen supply rates.

The G'DAY model does not purport to provide accurate results relevant to any particular practical situation; its parameter values are generally taken from the literature and are "best approximations" to likely values. It can be parameterized for particular situations, if enough experimental data exist, but its primary purpose is to provide insights into the relationships that exist between factors, such as nitrogen supply rates and atmospheric CO_2 concentrations, nitrogen concentrations in tissue, or biomass growth in relation to N-uptake rates and retranslocation. The model works on an annual time step and contains massive simplifications; it is a genuine attempt to describe the behaviour of a system in terms of its essential features. In this it contrasts sharply with models such as FORCYTE (Kimmins et al. 1999) and HYBRID (Friend et al. 1997; see below) that attempt to describe every detail of a (forest eco-)system at several organizational levels over short time steps. G'DAY provides a tool that can and is being used to bring clarity to discussions about the effects of climate change on forests and sustainability in terms of nitrogen supply and cycling.

Academia

Models developed primarily for the purpose of understanding mechanisms and the interactions between processes, possibly across different organizational levels, are valuable members of the congregation of forest models. A number of those already mentioned would qualify as "academic" in this sense, as well as being potentially applicable to some practical problem. Here I will consider only four models that serve to illustrate the genre.

Thornley's (1991) transport-resistance model of forest growth and partitioning applies the transport-resistance approach, originally developed by Thornley (1972) for crop plants, to forests. This is coupled with representation of growth in terms of the size and activity of meristems. The model has five compartments and is based on carbon and nitrogen pools and fluxes. The appendix to his paper presents three pages of parameters and state variables and four pages of equations, which suggests that it would be very difficult to reproduce and work with this model without help from Thornley or having the code provided by his institution. Nevertheless, the model produces plausible curves of the time course of the growth of various components of the simulated forest and clearly provides interesting and informative responses to stimuli. Thornley concludes his paper by arguing that the transport-resistance approach is scientifically sounder than empirical or teleonomic (goal-oriented) approaches and that a framework has been provided that permits extension to tree geometry, competition, self-thinning and regeneration, and soils in relation to nutrients and water supply. Clearly, if he is correct about all this, and his model could be produced with a suite of default parameters in a relatively simple package usable by people with a range of skills, then it is a very important work. We must assume that development will continue, and in time, the Edinburgh Forest Model (as it is now called) will become widely available. An example of analysis using this model is provided by Cannell and Thornley (2001).

The pipe model, deriving from Shinozaki et al. (1964), has been applied by Valentine (1985) as a means of defining the structural framework for a detailed derivation of the carbon balance of a tree. Growth of the tree is measured in terms of mean stem length (from leaves to feeder roots), basal area, woody volume, and total (carbon equivalent) mass. The model includes concepts such as active and disused pipes. The rate of biomass production is estimated as the rate of production of substrate minus the rate of maintenance respiration. The rate of use of substrate by each component is calculated separately. A recent paper (Valentine 1999) provides mathematical detail for this model (called PIPESTEM) and a series of simulation curves based on calibration using data from a loblolly pine stand in North Carolina. Valentine notes that estimation of precise error will require precise sampling methods to estimate the dry matter and longevity of fine roots and respiration rates of both fine roots and transport roots. Given the immense technical difficulties associated with those measurements, this requirement suggests that PIPESTEM will not be precisely tested in the forseeable future. PIPESTEM has a number of adjustable parameters and rate constants, although, conceptually, this model would probably be easier to parameterize than the Thornley model. The model, like the Thornley model, could, presumably, be used to explore the consequences of various hypotheses about tree structure and physiology, even without calibration against a detailed set of measurements.

CenW, produced by Kirschbaum (1999), is a comprehensive model of the growth of monospecific, even-aged stands that attempts to deal with all the major processes involved in CO_2, water and nitrogen fluxes, foliage dynamics, wood production, and stand architecture. CenW models carbon gain using a canopy photosynthesis model incorporating equations that deal with photosynthesis at the level of the cell enzymes; it uses a detailed stomatal response model and calculates evapotranspiration and stand water balance, which includes complex carbon allocation routines constrained by height–diameter relationships, soil N dynamics, and N uptake and allocation by the plant. The model has been parameterized using the comprehensive data set available from a major experiment carried out on *Pinus radiata* in the Australian Capital Territory (Raison and Myers 1992) in which all the biophysical measurements needed by CenW were made over a number of years. It runs on a daily time step and was tuned to produce results that matched those from the experiment. Kirschbaum used CenW to carry out sensitivity analyses to investigate responses to varying values of driving variables and parameter values. He has also used it to make simulations of wide-scale forest growth and response to environmental conditions. CenW was not designed as a tool for management but is useful as an attempt to link in one model all the biophysical processes considered important in the growth of trees and timber production. Its parameterization for other stands will be difficult because of the model's demands for data, but the concepts and formulation must be of value and provide insights into process interactions and the basis for simplification or further developments in this area.

Friend et al. (1997) produced an immensely detailed model of ecosystem dynamics, focussed primarily on trees, so it can legitimately be considered a forest model. HYBRID aims to couple carbon, water, and nutrient cycles in the soil–plant–atmosphere system. It is aimed at predicting the consequences of climate change in terms of GPP and NPP, heterotrophic (soil) respiration, latent heat flux, total carbon biomass, and annual maximum L^*. It also predicts the probable dominance of particular plant types. HYBRID operates on daily and annual time steps. It consists of a large number of submodels, including radiation and energy balance, photosynthesis, respiration, stomatal conductance, soil nitrogen dynamics, nitrogen uptake and allocation, carbon allocation, tree phenology, and hydrology. The many parameter values needed are gleaned from the literature and various data bases. Friend et al. demonstrate that using climate for a site in Pennsylvania, U.S.A., HYBRID produces "stable and sensible values". The model contains many different feedbacks, and the authors point out that it neither results in the decay of the ecosystem to no stored carbon nor overshoots. This model is clearly not intended to be used in any operational or decision-making context in relation to forestry, except insofar as it may contribute to evaluations of the probable impacts of climate change. (In this context it has been included in comparisons of the performance of a series of dynamic global vegetation models (Cramer et al. 1999).) In view of the number of parameters and feedbacks it is not obvious that it would provide clear results from scenario analysis of the type carried out by Kirschbaum et al. (1994), using G'DAY. However, it may have value as a framework within which to evaluate alternative versions of some of the submodels or for comparison with much simpler models.

Summary of the state of the art

The brief survey above of some of the PBMs currently available, which could either be used directly or readily adapted for various purposes, leads to the conclusion that in relation to the information requirements of mangers in the forest industries, the use of mixed process-based and empirical models will lead to significant improvements in model flexibility and predictive power. Models such as FOREST-BGC, 3-PG, and PROMOD have demonstrated that it is possible to calculate NPP accurately and allocate it to stems. Competition and the generation of tree size distributions can be represented using established empirical models. If we used a canopy model, based (for example) on the linear relationship between absorbed photosynthetically active radiation and biomass production, to provide the NPP constraint for the canopy as a whole and combined this with the procedures used to estimate the growth of different species, or competition between individuals, in the gap or succession models, it should be possible to produce relatively simple models to simulate the growth of mixed species stands. This is essentially the approach adopted in HYBRID, but that model would need to be massively simplified to be of any value as a practical tool.

G'DAY (Comins and McMurtrie 1993), and the approach used by Dewar and McMurtrie (1996*a*, 1996*b*) are relatively abstract models (mathematically stated hypotheses) that meet the criterion of representing the essential features of the system. They have value as aids to decision-making and policy formulation, because they allow exploration of the implications of the hypotheses they represent.

Challenges and the future

The major scientific challenges we face in our efforts to improve forest models are (arguably), the questions of carbon allocation, and the nutritional problem. The matter of spatial variation, which essentially relates to scaling, also needs a great deal of attention. The major operational challenge is a matter of communication: scientists and managers have to sit down together and find common ground. It is apparent, from the examples given above of models purporting to meet (some of) the information needs of forest managers, or clients in the broader public community, that few models are well tailored to these needs. It seems that in the case of PBMs, the process of model development seldom starts with the needs of the end user: there is not much evidence that the questions to be addressed, the accuracy required of output variables, or the number and availability of parameter values, are matters of primary concern to most model builders.

Carbon allocation

We can deal with carbon allocation at a practical level using allometric relationships, as the hybrid models do (Sievänen 1993; Landsberg and Waring 1997; Battaglia and Sands 1997; Korol et al. 1996; Ditzer et al. 2000), in various ways. There are also various schemes using fixed relationships and functional constraints between plant parts (Friend et al. 1997; Mäkelä 1997; Kirschbaum 1999). Thornley (1991) has put forward the most fundamental mechanism. Unfortunately, his procedures have massive parameterization problems, and there seems to be little prospect the transport-resistance model will be widely adopted or even well-tested in the near future. (Testing procedures would be difficult; see Mäkelä et al. (2000), for discussion.) Nevertheless, it is important that this question be attacked at that level, perhaps through experimentation under controlled conditions, using detailed physiological techniques and chemical analysis. With the advent of modern technology, such as the use of clonal material for intensive plantations, it is becoming increasingly important that we have models soundly based on physiological processes so that the potential of new technology can be evaluated. For example, what can tree physiologists tell genetic engineers or biotechnologists about the factors controlling carbon allocation in trees? Is this a profitable avenue for exploration? In cereals, which have been subjected to far more intensive breeding over many years than trees, much of the yield gain in modern varieties has come from improved harvest indices; i.e., the ratio of stem and chaff to grain weight has been considerably reduced (Austin 1980). Is it possible to improve the yield of plantation trees in the same way? We need to be able to explore this question thoroughly with models to provide guidance to the biotechnologists.

Nutrition

It is ironic that although nutrition has probably received more attention than any other aspect of forest production, our ability to describe soil nutrient status in terms that allow us to simulate plant responses to nutrition with any degree of surety remains poor. Models such as 3-PG and PROMOD rely on fertility indices, based on information about soil chemistry and organic matter, and can be calibrated, but do not include nutrients in any mechanistic sense. FORCYTE (Kimmins et al. 1999) includes simulation of the whole nutrient cycle (including within-plant and geochemical cycling), plant competition for nutrients, and estimation of nutrient abundance in relation to site quality. This is very ambitious; it remains to demonstrate rigourously, for a number of forest types and situations, that the simulations reflect reality and that the various submodels involved can provide accurate predictions of nutrient cycling and its effects on tree growth in particular forests. Another very ambitious attempt to simulate processes operating during the genesis of soils is incorporated in a model outlined by Levine et al. (1993); whether and how this is testable, and how the results are reflected in plant growth, is not yet clear. Their model, like many others, incorporates organic matter decomposition and nitrogen mineralization routines. Most models that attempt to deal with nutrition have focussed on nitrogen, both because of its importance for photosynthesis and because the N mineralization process is amenable to modelling. There seems little prospect, pro tem of doing anything more with phosphorus and potassium than estimating the amounts in the soil by some standard method of soil chemistry, and devising a soil nutrient supply index based on these measurements and cation exchange capacity.

As noted earlier, the CENTURY model (Parton et al. 1988, 1993) is commonly used to estimate N mineralization and, hence, the amount of N available to the plant. CENTURY has been tested against field data (Parton et al. 1993), but it is difficult to obtain the data needed to run it for a particular location and to decide on the (many) parameter values. This model undoubtedly provides a useful tool for analyses of general system behaviour and relationships. Comins and McMurtrie (1993) used a modified version to provide rates of N mineralization from soil organic matter and simply specified the N uptake rate by trees as proportional to the N mineralization rate, assuming trees are N limited. Dewar and McMurtrie (1996*a*, 1996*b*) assumed that nitrogen uptake rate by trees depends on the rate at which soil mineral nitrogen is made available and on root carbon. Kirschbaum (1999) used a more complicated scheme that included N cycling in the ecosystem and re-translocation in the trees. Friend et al. (1997) used a modified version of CENTURY; N uptake in HYBRID was proportional to fine-root mass, mineral soil N, and plant C:N ratios. All of these ideas are defendable as mechanisms in models, but none of them are readily applicable in operational environments.

The challenge for the future development of forest models lies as much with experimenters as with the modellers; there is a need for detailed research on uptake mechanisms, in controlled environments, with measurements designed specifically to test particular hypotheses as expressed in models. A practical alternative for stand models is suggested in the next section. We should also note the possibility that it will be possible to use satellite imagery to estimate canopy chemistry (see Matson et al. 1994; Martin and Aber 1997).

Sustainable management

Sustainability may be interpreted in biological, ecological, or economic terms. I will consider only management for biological sustainability, which we may define as management that does not result in losses of soil nutrients, degradation of soil structure, or loss of biodiversity over a long period of time; forests should be managed so that they remain in steady state with respect to these characteristics. Essentially sustainability means that rates of off-take or loss must not exceed replacement rates in the case of nutrients. The paper by Dewar and McMurtrie (1996*b*) provides an excellent treatment of the principles that are further developed by Dewar (2001) and in a number of papers in Carnus et al. (2001)

Spatial heterogeneity

Most carbon balance type models are written for homogeneous stands. The gap or succession models, which contain stochastic elements, particularly in relation to regeneration, deal with a number of plots and so can provide stand dynamics and data amenable to statistical analysis. However, for this reason, they are difficult to test.

The spatial heterogeneity in forest stands, particularly natural stands, is considerable, so the sampling problem is always severe. Tickle et al. (2001*a*, 2001*b*) demonstrated that given appropriate climate data and adequate information about soil fertility and water-holding capacity, the 3-PG model could be used to estimate growth and yield over a large area. The use of satellite data to provide input information for models is an important development, often overlooked because people tend to assume that the primary purpose of satellite imagery in relation to land surfaces, is mapping. This is a major misconception. We have already noted that 3-PG (Coops and Waring 2001*a*, 2001*b*) and FOREST-BGC (Running et al. 1989) have been used with satellite data providing estimates of leaf area index and (or) absorbed photosynthetically active radiation. Coughlan and Dungan (1997) provide a complete description of an ecological simulation system based on satellite imagery and the FOREST-BGC model.

The use of satellite imagery allows evaluation of the variance between pixels and imposition on those pixels of slope and aspect corrected radiation, temperature, and vapour pressure deficit (Coops et al. 2000; Running et al. 1987) leads to spatially and temporally explicit outputs at the scale of the input surfaces. A major difficulty in this sort of analysis is, very often, soil data: both water-holding capacity (Running 1994) and fertility. Coops and Waring (2001*a*) demonstrated that the 3-PG model could successfully predict both stand growth and seasonal water deficits for 18 precisely located study sites in the Siskiyou Mountains, Oregon, for which detailed information on soil water-holding capacity and soil fertility were available. Yet, applying the same model to 492 forest measurement plots across 54 000 km^2 in southwestern Oregon, Coops and Waring (2001*b*) obtained poor results because of local variation in climate, soils, and plot locations. When the sample plots were grouped within 14 different forest types the model accounted for 82% of variation in annual increments.

The Coops and Waring (2001*b*) study raises the question of methods of assessing stand volume, and changes in stand biomass, by means other than permanent plots. An option that could provide considerable information about large areas might be to make measurements of stem number, diameters, and height in plots of standard size at prespecified distances along transects. Soil samples could be taken at each location and measurements of L^* made using nondestructive techniques. No attempt would be made to establish permanent plots; the objective would be to obtain sufficient measurements to allow statistical evaluation of variation about spatial mean values. Transect-based surveys are greatly simplified by the availability of global positioning systems (GPS). It would clearly be of considerable value if such surveys could be repeated at intervals of a few years.

Communication

For any model to be applied as a practical tool it has to be tailored to the problem to be addressed. This may seem heretical to some scientists, imbued with the belief that good science should produce information of universal value, which, it is assumed, will seep into the consciousness of potential users by a process of intellectual osmosis. This is not an efficient way of propagating knowledge. Certainly there is a case to be made for relatively abstract research concerned with increasing our understanding of systems and the way they work, but to translate this understanding into results of value in the “real world”, modellers have to sit down with practitioners, analyse their problems and requirements, and adapt the best-suited available models to those requirements. This should include devising methods to test the results. Furthermore, formulation of models to provide practical information is not inimical to good science; the procedure will inevitably reveal problems of considerable scientific interest that should be solved to improve the model(s). It is an iterative process.

The future

The future of wood production should lie in plantation forestry, although clearly the complete phasing out of logging in natural forests may lie many years away. Plantation forestry offers the opportunity for tree crop improvement by breeding and biotechnology for intensive culture (fertilization, weed and insect control, stem population control, etc.) and short rotations. Models must be capable of predicting growth rates and yields in areas where plantations have not previously been grown and of providing estimates of the effects of variations in weather and different management (e.g., cultivation resulting in nitrogen mineralization and release, soil management to influence water-holding capacity). They must also provide guidance to tree breeders and silviculturalists (e.g., what are the effects of pruning? See Pinkard et al. 1999).

An example of the operational use of a process-based model illustrates a number of points about future directions. The 3-PG model has been adopted by Aracruz Celulose (AC), a large company in eastern Brazil, producing eucalyptus pulp for its own mills from its own plantations. The company has about 140 000 ha of plantations and is increasing that area. Rotation length is 7 years. There is a large and expensive mensuration program.

AC has all its lands digitally mapped (soils and topogaphy). The company operates a network of automatic weather stations. 3-PG has been parameterized against detailed data, including physiological measurements, collected in several experimental areas, and tested against plot data from different regions (Almeida et al. 2003*a*, 2003*b*). Model outputs (stem volume, mean diameter) will provide input to conventional models that will apply stem size distributions and calculate wood quality in terms of parameters such as piece size. The mensuration program is to be reduced from thousands of plot measurements per year to a few hundred, sampling the soil and climate regions across the AC estates, with considerable cost saving. These plots will provide the data needed to produce and check the wood-quality variables, and when harvested they will provide data against which to check model productivity predictions. The thinning routine in the model will be checked against reality. The 3-PG model can be run for any forest unit at any time, providing an estimate of standing volume for reporting, economic evaluation, and planning purposes. It has already been used to analyse changes in productivity across the estates and determine whether these are attributable to weather conditions or management. Experimental plots, with different fertilizer treatments and, in some cases, irrigation, will be maintained at several locations, providing additional, detailed data to check and calibrate the model. Research is being focussed on the question of fertility and on reasons for differences between clones.

On the question of nutrition, in view of the doubts and difficulties concerning N-mineralization models, Paul et al. (2002) have developed a new empirical model (soil nitrogen availability predictor; SNAP) to predict N mineralization across a wide range of sites. The base rate of mineralization for any site is estimated from laboratory incubations of disturbed soil under near-optimal conditions of temperature and moisture. Using submodels to calculate soil temperature and water content in three layers (the inputs required are air temperature, L^*, or an estimate of canopy cover, rainfall and radiation, and soil physical information), and using the outputs of those submodels to calculate dimensionless modifiers, daily rates of N mineralization are calculated from the base rate. The model was developed using detailed data from mineralization studies at 39 sites across Australia. Some of the data were "quarantined" from development and retained for testing. The model accounted for more than 70% of the variance at test sites.

The Paul et al. N mineralization model provides a practical means of assessing site fertility. Soil samples can be bulked to provide area means, and the laboratory incubation procedures can be standardized. In an operational context foliage N should be determined, as is routine in many companies and related to calculated N mineralization. This should provide a means of estimating the variable of primary importance, canopy N, which is the major factor determining ε (see Ågren 1985; Field and Mooney 1986; Comins and McMurtrie 1993; Kirschbaum et al. 1994; Dewar and McMurtrie 1996*a*, 1996*b*). Scaling canopy N to maximum canopy N will provide the nutrient modifier for ε.

Concluding remarks

Process-based simulation models are at the stage where they can be used as management tools to predict growth and yield of forest stands. To optimize their effectiveness, and to engender confidence in users, the scientists who develop and work with these models must consult, and work closely, with the prospective model users. For managers concerned with production forestry it will invariably be necessary to combine the PBM with conventional statistical analyses; if the PBM produces aboveground biomass as its primary output, then this will have to partitioned into stem numbers and stem size distribution. If the PBM produces stem numbers it may only be necessary to combine it with empirical analyses of stem size distribution. PBMs can provide quantitative estimates of the potential growth of plantations in new areas and of the effects of climate change. They are important tools for heuristic analysis to answer the "what if" questions in relation to factors such as management actions, insect attack, or drought. Concerns about imperfection are irrelevant; scientists tend to be strongly aware of the shortcomings of their models, so they are sometimes reluctant to release them for practical use. It is clearly important to be aware of problem areas that may lead to errors, but many imperfect models will be better than guesswork or rules of thumb, so let us use them. Improvements will follow.

It is axiomatic that any model intended as a management tool should be as simple as possible. The number of parameters must be reduced to the minimum commensurate with the essential features of the problem and realistic responses to the variables being analysed. Complex, multiparameter models tend to remain as research tools within the scientific community, and even there they tend to be used only by their creators and, perhaps, a small circle of colleagues. It is also important that models should be balanced; it does not seem justifiable, for example, to calculate photosynthesis at the leaf level, in terms of enzyme concentrations, in models intended for application at regional or even global scales. In this respect the G'DAY model provides an object lesson. There is an important role for complex models that attempt to describe all the important processes involved in tree and stand growth, as tools for developing simplified versions that might be more widely used.

The question of software availability has not been discussed but should be mentioned. Many models are programmed by the scientists who develop them, and the software is never produced in a form suitable for release and use by others. Scientists are often hesitant to do this, because it involves them in some risk; they are nervous about the way the models might be used (or misused), they know they are imperfect and are reluctant to commit themselves, and they do not want to allow time to provide technical support for users. These are matters of personal and organizational decision, but if a model is not released in usable form, with supporting notes, and preferably a user manual, then its use and application will remain limited. The World Wide Web now makes it simple to distribute software. In this respect the example of Sands (2001), in relation to the 3-PG model, should be noted.

The question of testing conventional forest growth models was discussed in detail by Vanclay and Skovsgaard (1997). PBMs can be tested at the level of their submodels or submodel parameters, or at the level of their outputs in relation to empirical data relating to the whole system. Mäkelä et al. (2000) provide comment on these matters. Scientists are, rightly, normally concerned to achieve considerable precision when models are tested against particular data sets, but modellers and users should have a clear idea of how accurate a model must be to meet their requirements. For wide-scale use we cannot expect a high degree of precision in relation to individual sites, but we need assurance that the results are unbiased, so that spatial means can be trusted. It is also important to be aware of the variability and uncertainty associated with measurements in forest plots, repeated at (sometimes) long intervals. Even matters like plot location may be uncertain (see Coops and Waring 2001*b*), although with the availability of cheap and accurate GPS, this should not, nowadays, be a problem.

Lastly, it is worth remarking that forest modellers should exploit the techniques of modern technology and contribute to it. Our models should be able to simulate processes that might be modified by biotechnology; we must make use of satellite technology, GPS, and the World Wide Web.

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