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Modelling the Sustainability of Forest Production and Yield for a Changing and Uncertain Future

by

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Abstract

The expected growth of the human population to about 11 billion sometime within the next rotation of most northern temperate forest crops will put greatly increased and varied demands on today's forested lands. Development of the timber resources on those lands that remain dedicated to timber production must be demonstrably sustainable if forest management is to help arrest rather than aggravate the continuing deterioration of the global environment, and if managed forests are to be a carbon sink rather than a carbon source with respect to the global "greenhouse effect". Unfortunately, the experience-based models traditionally used by foresters cannot make accurate predictions of future forest growth, yield, and carbon balance for the altered growing conditions that are expected to accompany this increase in human numbers. These tools are therefore unsuitable as a means of assessing the sustainability of site productivity under current or anticipated future forest management practices and the expected future soil, climate, and biotic conditions. It is time for foresters around the world to confront this issue and to develop and use more ecologically-sensitive, ecosystem-level stand growth and yield models.

Knowledge-based, process-simulation stand growth models have many theoretical advantages, and are the only way of predicting future forest growth and carbon budgets on a particular site in the absence of accurate data on the past growth of forests on that site. However, such models have generally had significant practical limitations as an alternative to traditional forest yield models. They have either been too simple, or, if sufficiently complex, have had unacceptably large calibration data requirements, which has limited their portability. This has restricted most process-based simulation models to research and educational applications.

An alternative approach which combines both the experience-based and the knowledge-based approaches offers a more practical alternative. The combination of "historical bioassay" and process-based modelling approaches into "hybrid simulation"

Résumé

En passant à environ 11 milliards d'êtres humains à un moment quelconque de la prochaine rotation des peuplements forestiers dans les régions tempérées du Nord, la population du globe exercera une demande accrue et plus diversifiée sur les boisés que l'on connaît aujourd'hui. Pour que la gestion forestière mette un frein à la détérioration de l'environnement global au lieu de l'aggraver et pour que les forêts aménagées absorbent le carbone au lieu de le libérer, ce qui accroîtrait "l'effet de serre", on doit prouver qu'il est possible d'exploiter les ressources forestières de façon durable sur les terres réservées exclusivement à la production du bois. Malheureusement, les modèles, basés sur l'expérience, auxquels recourent habituellement les forestiers ne permettent pas des prévisions précises sur la croissance, le rendement et le bilan carbonique des forêts dans les nouvelles conditions végétales qui devraient accompagner la croissance démographique. On ne peut donc s'en servir pour évaluer la vie productive d'un site en fonction des pratiques de gestion forestière actuelles ou futures et les conditions pédologiques, climatiques et biologiques à venir. Il est temps que les forestiers du monde s'attaquent à ce problème et élaborent puis mettent en pratique des modèles écologiquement plus sensibles et couvrant tout l'écosystème sur la croissance et le rendement des peuplements.

Les modèles sur la croissance des peuplements qui reposent sur les connaissances acquises et la simulation des procédés présentent de nombreux avantages théoriques et demeurent la seule façon de prévoir la croissance des forêts et le bilan carbonique à venir à un endroit donné, en l'absence de données précises sur les peuplements forestiers qui se sont succédés à cet endroit. Toutefois, ces modèles présentent aussi d'importantes limites sur le plan pratique, comme solution de rechange aux modèles traditionnels sur le rendement forestier. En effet, soit ils s'avèrent trop simples, soit, s'ils sont plus complexes, ils nécessitent une somme inacceptable de données pour leur adaptation, ce qui en réduit l'utilité universelle. C'est pourquoi la plupart des modèles de simulation basés sur les procédés ne sont surtout utilisés qu'en recherche et dans l'enseignement.

Une autre approche qui combine celles basées sur l'expérience et sur les connaissances s'avérerait plus pratique. En combinant les "données biologiques

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stand models can provide a means by which to rank the most probable outcomes and the sustainability of alternative stand-level management strategies under a variety of possible future growing conditions.

The accuracy of most forest management and forest economics models ultimately depends on the accuracy of stand-level growth models. As the world experiences increasing problems of air pollution (acid rain and the greenhouse effect), soil degradation, and deforestation, there is an urgent need for foresters to use ecosystem-level growth models that are sensitive to human-induced and naturally caused environmental changes. Use of such models is a necessary prerequisite to good stewardship of forest land and our legacy to future generations.

historiques" et la simulation des procédés pour obtenir un modèle "hybride" des peuplements, on pourrait évaluer les conséquences les plus probables et la pérennité des différentes stratégies de gestion en fonction des diverses conditions de croissance susceptibles de se manifester dans l'avenir.

En fin de compte, la précision de la plupart des modèles de gestion et d'économie forestières dépend de la précision des modèles sur la croissance des peuplements. Face aux problèmes mondiaux croissants de pollution atmosphérique (pluies acides et effet de serre), de détérioration des sols et de déboisement, il est urgent que les forestiers se servent de modèles de croissance basés sur l'écosystème et plus sensibles aux changements anthropogènes ou naturels de l'environnement. L'application de tels modèles est un pré-requis à une saine gestion des terres forestières et du patrimoine que nous laisserons aux générations qui doivent suivre.

Dedication

This paper is dedicated, with great respect, to the memory of Dr. Peter J. Rennie, who has been an inspiration to those working on long-term site productivity since his pioneering work in UK in the early 1950's. His more recent concerns over acid rain and the greenhouse effect provided leadership to forest scientists working on these topics. He will be missed, but remembered with respect.

Introduction

The single most important factor affecting the future of the world's forest is the continuing growth of the human population, to an anticipated level of about 11 billion (World Bank 1984, Repetto 1987, Brown *et al.* 1988). This doubling of the present (1989) population is expected to occur within the time necessary for coniferous crops planted on most Canadian clearcuts in 1990 to reach harvestable condition. Human population growth will lead to a reduction in the area of forest, and an increase in the demand for timber products (Council on Environmental Quality 1980, Industrial Working Party 1982, Ford 1983), renewable biomass fuels, chemical feedstocks, clean water, water storage, transportation and power-transmission corridors, recreational experiences, and wilderness and wildlife values from the remaining forest. More forest resources will be demanded from a forest land base that is increasingly restricted to less productive sites with poorer soils (Thorud 1983). Accompanying the population growth, air pollution will probably get a lot worse before it gets better, with attendant problems of acid rain, ozone damage to vegetation, and climate change due to the accumulation in the atmosphere of "greenhouse gasses" (Shands and Hoffman 1987, Harrington 1987, Hennessey *et al.* 1987, Bolin *et al.* 1986, Bell 1986, Morrison 1983, 1984, Binkley *et al.* 1989, Smith and Tirpak 1989).

The United Nations reacted to these concerns by appointing the World Commission on Environment and Development under the Chairmanship of Norway's Prime Minister, Dr. Gro Harlem Brundtland. A major conclusion of their final report "Our Common Future" (World Commission on Environment and Development 1987) was that whilst the industrialized countries bear a heavy responsibility for the present and past deterioration of the global environment, the greatest long-term threat to the environment comes from

poverty in the rapidly-growing populations of third world countries. Unless this issue of global poverty can be addressed, the prospects for sustaining or improving the present global environment are not very good. The UN Commission concluded that the best hope lies in the wise and sustainable development of renewable resources. Only by doing this can the question of global poverty and unregulated human population growth be resolved. Resources must be developed, but this development must be sustainable, and demonstrably so. The development of resources must also be conducted in a manner that does not threaten other aspects of the global environment.

The demonstration of sustainability requires the use of local, regional, and global resource development planning tools that are capable of predicting the probable long-term consequences of current strategies of resource use. It was suggested at a IUFRO Working Group meeting² in 1987 that stand-level sustainability in temperate forestry involves time scales equal to at least three rotations of temperate tree crops (i.e. 150–300 years). The objective of this paper is to show that currently-used traditional stand-level forest growth and yield models are inappropriate as tools by which to assess the stand-level sustainability of current forest practices in most areas of the world, and to propose an alternative stand-level growth and yield modelling strategy. More complete documentation of the arguments presented here have been presented elsewhere (e.g., Kimmins 1985, 1986, 1988; Kimmins and Sollins 1989).

Traditional Growth and Yield Stand Models in Forestry: Experience-based Prediction of Forest Growth and Yield

Ever since the method was formalized by German mensurationists in the late 1700s, the standard method of stand-level yield prediction in forestry has been the forward projection of past patterns of forest growth (Assmann 1970). This method, which constitutes a "historical bioassay" of the growth potential of a site, has the great advantage of not being limited by our still incomplete knowledge of the ecological and physiological determinants of growth, or by research budget and human resource limitations which constrain our attempts to improve this knowledge. Yield tables, and the yield

²S1.02.09 "Management Impacts on Forest Site Productivity". PNW Subgroup.

equations or mensurational models based thereon, are implicitly ecosystem-level models, because the historical record of stand development and biomass accumulation integrates the sum total of edaphic, climatic, and biotic factors that has affected the trees over the entire rotation.

It is hard to imagine a more believable and practical stand-level growth and yield prediction tool than the traditional mensurational model *if, and only if*, one assumption is satisfied: that the future growing conditions are sufficiently similar to those that pertained over the rotation which was the basis for the model that future growth will indeed be similar (Figure 1). Within one rotation of the formalization of the yield table method, German mensurationists were reporting that on some sites and under some management regimes, the predictions of mensurational models can be unreliable (Ebermeyer 1876, Rennie 1955, 1957, Assmann 1970). This conclusion was the result of yield declines in north German pine forests in which litter (needles and branches) was raked annually to provide fuel, bedding for cattle, and organic fertilizer (e.g. Wiedemann 1935). Since that time, yield declines as a result of inappropriate management practices have been reported from elsewhere (e.g. second rotation yield declines in radiata pine, South Australia (Keeves 1966, Squire *et al.* 1979, 1985, Farrell *et al.* 1981, Squire 1983), and there are many reports of yield increases that have resulted from management-induced improvements in growth conditions. Clearly, the historical bioassay approach is unsuitable as a basis for yield prediction if the future is significantly different from the past, its undeniable value for unchanging conditions notwithstanding.

Will Future Growing Conditions be Significantly Different From Those of the Past?

The evaluation of traditional approaches to forest growth and yield thus depends on whether or not one believes that the future growing conditions will be significantly different from those of the past. Recent predictions about global climate change (e.g. Bolin *et al.* 1986, Shands and Hoffman 1987, Harrington 1987, Schneider 1989, Schneider and Londer 1984) provide persuasive evidence that climates will change significantly within the next rotation of northern conifers. Although there is still great uncertainty about long-term climate predictions at a regional level, and about the role of clouds there appears to be a broad degree of unanimity amongst climatologists that the average world climate will increase between 1.5 and 4.5°C, that the effects will be much greater at higher latitudes (especially in the northern hemisphere) than near the equator, and that winter warming will generally be greater than summer warming. Despite the regional uncertainty, which will probably continue for at least the next decade, these generally-agreed-upon global predictions are sufficient on their own to cast grave doubts about the validity of the historical bioassay in many parts of Canada. Cold, northern forests may experience better growth, while some southern forests may be displaced by grassland. Species requiring winter chilling may be lost in southern or coastal areas (Kimmins and Lavender 1989). The anticipated winter warming and increased variability in winter climates can be expected to result in an increased incidence of bud damage and leader death, with negative implications for tree form (c.f. Cannell 1989, Cannell and Smith 1986, Kimmins and Lavender 1989, Lavender 1989, Van der Kamp and Worrall unpubl. mss.).

In addition to climate change, the apparent trend towards more complete utilization of forest biomass (harvest of all above-ground biomass, or of complete trees including stumps and large roots) on shorter rotations using

mechanized harvesting poses the risk of significant short- and long-term change in soil organic matter and nutrient resources. Loss of soil organic matter has important implications for soil physical structure, soil biology, soil moisture and nutrient holding capacity, and susceptibility to erosion. These soil parameters, in conjunction with the total inventory and availability of nutrients, are major determinants of short- and long-term site productivity. Significant reductions in available nutrients due to intensification of management and biomass removals will require fertilization if productivity is to be sustained (Kenney 1980).

Although growth reductions due to nutrient loss have not been as widely documented as growth improvements due to fertilization, there is an increasing body of anecdotal and experimental evidence from research and long-term field trials that such growth losses do occur (e.g. Lundmark 1977, 1983, 1986, Andersson 1984, Squire 1983, Messina *et al.* 1985, Squire *et al.* 1985, Dyck and Skinner 1990), abundant evidence of slower tree growth on infertile sites than on fertile sites, and evidence that tree growth is limited by nutrient shortages in all the forest regions of Canada (Mahendrappa *et al.* 1986). Combined with the principles of forest tree nutrition (Ingsted 1987), site nutrient management (e.g. Binkley 1986), biogeochemical theory (e.g. Attiwill and Leeper 1987), and nutrient-based forest management or ecosystem models (Aber and Melillo 1982, Kimmins 1988, Kimmins and Scoullar 1979, 1981, 1983, Pastor and Post 1985, Ågren 1986), an unequivocal case can be made that significant nutrient depletion due to intensive biomass harvesting will reduce productivity on many forest sites. It has been suggested that many forest areas have the climatically-determined potential to grow at double or even triple the current rates (Axelsson 1983a, Gordon 1982, Gordon *et al.* 1982), but that the attainment of this potential is normally limited by inadequate nutrition (Axelsson 1983b, 1985).

Research with sewage sludge (e.g. Cole *et al.* 1985) and fertilizer applications (e.g. Barclay and Brix 1985) have shown spectacular growth responses on edaphically-dry sites in coastal British Columbia and Washington. The implications of this research are very important, because they suggest that ecophysiological, canopy-function models that invoke the direct effects of moisture on plant physiology as the major factor limiting growth (e.g. Running 1984, Spittlehouse and Black 1981) may be in error in some climates. Summer drought may well operate as much through soil biology and soil processes as through plant physiology and canopy function. If this is true, many dry sites may be more nutrient-limited than moisture-limited, and, with appropriate site nutrient management, may be capable of substantial net primary production. On the other hand, if these sites are in fact truly moisture-limited, it may not be possible to raise site productivity within the constraints set by stand-level production economics. Clearly, research is needed to clarify this issue.

Soil degradation can cause growth losses at the regional level by reducing the area available for forest growth, as well as by reducing growth on areas that remain forested. It has recently been estimated (Utzig and Walmsley 1988) that management-related soil degradation in British Columbia may be causing as much as \$80 million worth of lost forest growth annually, and that this loss is increasing by \$10 million a year. Although the data on which this estimate is based, and therefore its magnitude, can be questioned, the fact that soil degradation is occurring is unquestionable. Clearly there is a totally unacceptable level of soil degradation in the province (Lousier and Still 1988), a degradation that renders the predictions of traditional yield models highly suspect where it occurs.

Figure 1. The historical bioassay approach to yield forecasting. There is probably no better method if future growing conditions and management regimes are the same as those of the past rotation. However, the predictions produced by this method are unreliable if future conditions are different.

Climatic and edaphic changes are not the only factors that may alter forest growth and cause future growth and yield to differ from that of the past. The impact of biotic factors may also change. The abundance and species composition of non-crop vegetation may change from one rotation to the next (c.f. Nambiar and Zed 1980, Squire 1983), resulting in delays and/or reductions in crop tree development due to competition, allelopathy, physical interference, or the alteration of soil nitrogen status. The management-induced removal or increase of early-successional nitrogen-fixing species (e.g. alder) can reduce or augment soil nitrogen levels, with important consequences for tree growth (Binkley 1983). Management-induced alterations in the normal successional sequences of plant species can also have negative impacts on growth. Second rotation red alder crops may not grow as well as first rotation crops because of soil changes induced by the alder (acidification, N-enrichment, reduced P availability (Cole *et al.* 1990)). Repeated cropping of Douglas-fir without intervening occupancy of the site by other species such as alder can lead to serious root rot problems.³

If climate change occurs and causes increased physiological stress in trees, disease and insect problems may increase, with implications for growth and yield. If the climate becomes hotter and drier, fire may be expected to exact a greater toll, reducing regional forest yields both by reducing the area of mature forest, and, in some cases, by damaging the physical structure of the soil or its fertility.

Where one wishes to predict the short-term growth response of forest stands to silvicultural treatments, the traditional historical-bioassay approach may be acceptable and even optimal. It is unlikely that radical changes in growing conditions will occur in a stand within a 5-, or possibly even

a 10-year period, for example. However, short-term silvicultural responses are relatively uninteresting in Canadian forestry. It is the consequences of our management actions and silvicultural investments over the entire rotation that is of major importance (e.g. Lundmark 1977, Baskerville 1986, Kimmins 1986). Considering both the changes in environmental conditions (as noted above) and the changes in forest management that I expect will occur over the next 30–50 years (half a rotation on most sites: see Table 1), I do not believe that rotation-length yield predictions based on unmodified historical-bioassay models are credible.

Process-based Forest Growth Simulation Models: Knowledge-based Prediction of Forest Growth and Yield

The response of forest scientists to the shortcomings of the traditional approach to growth and yield prediction has been to develop models that describe, mechanistically, the processes that determine the quantity of economically-recoverable biomass. These models attempt to represent the major ecological and physiological factors that determine the proportion of solar energy that becomes stored as economically-harvestable production (i.e. yield: Figure 2). This is usually done by establishing relationships between growth-related parameters and a variety of abiotic and biotic determinants of net biomass accumulation, combining these relationships into a mathematical model, supplying the model with input data on the expected future values of these yield determinants, and running the model on a computer (Figure 3).

Theoretically, this is the ideal approach to the prediction of forest growth and yield because it has the flexibility

³B.J. van der Kamp, Forest Pathologist, Faculty of Forestry, Univ. of British Columbia, Vancouver, B.C., Personal Communication.

Table 1. Canadian forest management of the future

Some possible changes	Some possible consequences ¹
<ul style="list-style-type: none"> • Shorter rotations • Intermediate harvests (thinnings) • More complete biomass utilization • Slash and, in some cases, litter utilization • Greater mechanization • Greater control of non-crop vegetation 	Depletion of soil organic matter and nutrients " " " " " " Soil compaction and erosion Loss of species diversity and disruption of successional processes of soil and site recovery
<ul style="list-style-type: none"> • Wider spacing and pruning 	Increased competition from non-crop vegetation
<ul style="list-style-type: none"> • Greater use of N-fixing species 	Improved site N status and greater diversity of weed species
<ul style="list-style-type: none"> • Greater use of "nurse crops", alternating crops, and species mixtures 	Altered (generally improved) soil fertility and nutrient cycling
<ul style="list-style-type: none"> • Increased use of fertilization and use of forest as a "living filter" to recycle urban waste (sewage sludge and processed compostable domestic garbage). 	Improved soil fertility and organic matter levels.

Repeated cropping of the same species is expected to give rise to increased problems of diseases, insects, and in some cases, nutritional problems.

¹Some of the anticipated changes are expected to result in better growth and yield. Others are expected to have a negative effect.

to deal with altered future growing conditions. In reality, the enormous complexity involved in representing all the myriad processes that determine net biomass accumulation in harvestable biomass components over an entire rotation has generally limited such models to an educational and research role. In many cases, process-based models of forest growth have lacked one or more major determinants of growth. The reasons for this have included one or more of: the lack of an adequate scientific understanding of the processes involved, the lack of knowledge about a known process by the individual developing the model, the lack of data to calibrate the simulation of a known process, the objectives of a particular model (which may have been to model an individual process or subset of the ecosystem, rather than the entire rotation-length forest growth process), or the lack of access to a computer powerful enough to incorporate simulations of all known processes. However, accompanying the rapid increase in our understanding of forest ecosystems over the past two decades, there has been an increasing number of ecosystem-level models of forest growth (e.g. Mohren 1987, Barclay and Hall 1986) that do include a large proportion of the important growth-determinants, and eventually we may have process-based models that provide a practical alternative to the traditional historical bioassay model.

Although detailed, process-based simulation models offer the most flexible available technique for predicting yield in a changing and uncertain future, they also suffer from a degree of inflexibility. The various relationships between growth and environmental variables that such models are made up of are in essence a series of simple regressions (i.e. correlations). These regression relationships are valid for the past conditions under which they were established, but will not necessarily remain valid under plausible future conditions, because other growth-determining variables not represented in the regressions may change. Thus, even the most detailed process-based model may still perform unsatisfactorily under some circumstances.

The practical application of process-based models will probably be limited for some years to come by their heavy calibration data demands, which limits their portability and

restricts their use largely to research and education. This limitation has led to the development of a third approach to the prediction of future forest growth: hybrid simulation modelling.

Hybrid Simulation Modelling of Forest Growth and Yield

The inflexibility of the historical bioassay approach, and the often overwhelming complexity of the process-based simulation approach, has created a need for a new method of stand-level growth and yield prediction. This need can be satisfied by combining the two other approaches into a hybrid simulation model.

The hybrid simulation approach (Figure 4) assumes that the historical pattern of biomass accumulation is the best estimate we have of future growth of a species or community under unchanging growth conditions (c.f. Figure 1). It then asks the question, "can this historical pattern be repeated if certain growth-determining factors (e.g. nutrient availability, light competition) change in the future?" In most of the future scenarios one may wish to consider, only a subset of the major growth-determining processes or factors are expected to change. It is a less complex simulation task to modify the historical growth pattern according to a simulation of this subset than to simulate all aspects of ecosystem function that determine net biomass accumulation over the rotation, as must be done in an entirely process-based simulation model.

The first and best-known example of this approach is the JABOWA and FORET series of model, developed initially by Botkin *et al.* (1972), and elaborated by Shugart and West (1977), Aber and Melillo (1982), Weinstein *et al.* (1982), Shugart (1984), Pastor and Post (1985), and Smith and Urban (1988, see also Shugart *et al.* (1988), Burton and Urban (1989)). Smith *et al.* (1989), and Urban and Shugart (1989). The JABOWA series are gap models (Shugart and West 1980) designed to simulate forest succession over long time periods (many centuries), and this simulation approach has proven to be very successful for this purpose. These models have also demonstrated their value for use in predicting the effect of climatic change on forest plant community composition and succession (Solomon and West 1987, Pastor and Post 1988, Urban and Shugart 1989), and there have been efforts,

Figure 2. The major determinants of economic production (yield) in a forest ecosystem within a particular climatic regime. Clearly, the availability of site resources (water, light, nutrients) are critically important, both directly, and indirectly through their effect on the allocation of net photosynthates.

though less extensive than for the successional and climate change applications, to use the models to predict the long-term impacts of forest management on site productivity (Aber *et al.* 1979, Waldrop *et al.* 1986, Yarie 1989).

For unmanaged, multi-tree species forests in which minor vegetation (i.e. the understory) does not play a significant ecological role in determining site productivity, the earlier JABOWA-based models have much to offer in the simulation of succession. The more recent multiple growthform versions of ZELIG expand this capability to the simulation of early secondary successions following disturbance (Burton and Urban 1989, Smith *et al.* 1989). These gap models use a variety of multipliers to alter the historical pattern of growth of trees (represented in a growth equation that describes the growth of the species under ideal conditions for that species) regenerating naturally in small gaps created by the death of individual trees. The number and type of modifier varies between the different models in the series, but they include one or more of temperature, moisture, light, and nutrients. Some modifiers are calculated from input data; others are simulated dynamically within a model run. The successional development on a larger area is represented by conducting large numbers of individual patch simulations in which deliberately-introduced stochasticity in recruitment and

mortality results in different successional outcomes. The results of these individual gap simulations are then summed to represent the overall successional mosaic of the larger area.

Until recently, there was concern (Shugart 1984) that the model's simulations of the response of the vegetation to large-scale disturbance (fire, insects, clearcutting) may deviate increasingly from reality as the simulated area on which vegetation is removed deviates more and more from the small gap (e.g. 1/10 or 1/12 ha) that is assumed in the model structure. Thus, although the patterns of succession in a forest clearcut in 50 ha patches may differ significantly from succession in an unmanaged forest, the earlier JABOWA series models would simulate a similar pattern of succession for these two different scales of disturbance. The extent of this possible error has not yet been quantified rigorously to my knowledge. Recent and current modifications of the JABOWA approach (e.g. ZELIG: Smith and Urban 1988, Burton and Urban 1989, VEGOMAT: Smith *et al.* 1989) overcome several of these shortcomings of the earlier versions.

As the JABOWA series of gap models was being developed by US forest ecologists, the need for a more management-oriented hybrid growth and yield model led to

Figure 3. The process-based simulation approach to growth and yield prediction. This is a knowledge-based approach, and it has the flexibility to be able to make accurate predictions for changed future growing conditions.

the development of FORCYTE in Canada (Kimmins 1988, Kimmins and Scoullar 1979, 1981, 1983, Kimmins *et al.* 1990). The genesis of this development was the ENFOR (ENergy from the FORest) program developed jointly by the Canadian Forestry Service (now Forestry Canada) and the Department of Energy, Mines and Resources. The objective of the model was to examine the economic and energy cost-benefit performance of alternative forest energy plantation or other intensive biomass-for-energy management strategies. In satisfying this objective, it became necessary to develop a rather detailed simulation for forest ecosystem function (including canopy function, nutrient cycling, nutritional limitations on growth, competition for nutrients, and competition for light), and a simulation of secondary succession. The result was a hybrid simulation forest ecosystem management modelling framework that has proven to be applicable in a variety of forestry and agroforestry situations around the world. FORCYTE-11 has been the subject of several studies in Canada (Peterson *et al.* 1988, Moore and Meades 1988, Kurz *et al.* 1988).

The FORCYTE models have several capabilities that are not yet available in the JABOWA series. Conversely, the JABOWA - derived models have several abilities that are not provided in the latest FORCYTE version: FORCYTE-11. Most of these shortcomings are rectified in a new model, FORECAST (FORestry and Environmental Change ASsessmentT) which is currently under development. The choice of which of these models to use will obviously depend on the

combination of the particular objectives of the model user and the particular model's capabilities.

Brief Review of the Modelling Approach Used in FORCYTE-11, and a Summary of its Capabilities

FORCYTE-11 is an ecosystem modelling framework, rather than a specific model. It consists of three separate modelling activities: a "setup", an ecosystem management simulator, and a data analysis activity. The "setup" consists of four separate programs that simulate tree growth, growth of herbs, shrubs or simplified trees, growth of bryophytes, and a variety of soil processes. The function of these setup modules is to assemble a variety of empirical input data that define how the plant species to be simulated have grown, on their own, on sites varying in nutritional site quality in the past. This set of "historical bioassay" data are combined with input data that define the rates of various soil processes and some aspects of canopy function, to produce a set of indices of canopy function, photosynthate allocation, biomass turnover, stand self-thinning, branch self-pruning, nutrient cycling, and soil processes. These indices are then passed to the main program where they are used to simulate stand growth, succession and ecosystem change.

This main program (MANAFOR) is an ecosystem management simulator, in which the user can represent forest ecosystems of various levels of structural and functional complexity, from a single-species stand with a representation of intra-specific competition for light but no soil representation (not the intended use of the model), to a multi-storied, multi-species, multi-life-form plant community with representations of geochemical, biogeochemical and internal nutrient cycling, soil fertility, and competition for light and nutrients. Many of the major silvicultural practices can be represented, as well as several natural disturbance events (e.g. fire, defoliation). When fully calibrated, the model is capable of predicting biomass, yield, stand level economics, and the energy-efficiency of management for a wide variety of alternative stand-management strategies.

Further details of the structure and logic of FORCYTE-11 can be found in Kimmins (1986, 1988, 1990), Kimmins and Sollins (1989), Kimmins and Scoullar (1990), and Kimmins *et al.* (in preparation).

Conclusions

Although there is debate over the implications of the recommendations of the World Commission on Environment and Development, there is little disagreement over the need to ensure that all present and future resource use and development must be sustainable and demonstrably so. This consensus implies the need for planning tools with which to examine the sustainability of forest management. The traditional forest growth and yield prediction methods used in forestry are only credible in this role if one assumes that future growing conditions (defined by the combination of management practices and environmental conditions) will remain very similar to those of the past. The evidence in favour of no future change in growing conditions is very weak in comparison to that indicating significant change in soils, climate, fire, and biotic conditions. If one accepts this conclusion, one must also accept the need for a new generation of stand-level forest growth and yield prediction tools. The best available alternative that has been developed so far would appear to be the hybrid simulation approach.

Figure 4. The hybrid simulation approach to growth and yield forecasting. This method combines the historical bioassay and process-based simulation approaches, and takes advantage of the merits of both component approaches.

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