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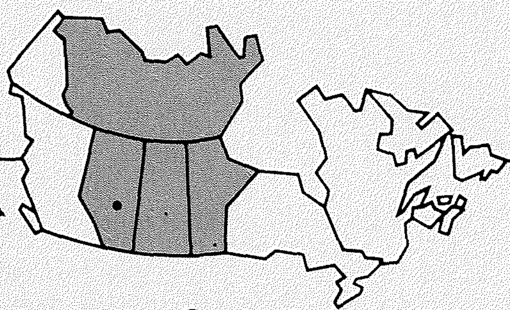
Forest Modeling Symposium

B.J. Boughton and J.K. Samoil, editors



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FOREST MODELING SYMPOSIUM

Proceedings of a symposium
held March 13-15, 1989, in Saskatoon, Saskatchewan

B.J. Boughton and J.K.Samoil, editors

INFORMATION REPORT NOR-X-308

FORESTRY CANADA
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ABSTRACT

The Forest Modeling Symposium was held March 13-15, 1989, in Saskatoon, Saskatchewan. Twenty-seven papers were presented on the role of forest modeling, past and current modeling activities, new directions in modeling, and modeling in other resource sectors.

RESUME

Le Symposium sur la modélisation forestière s'est déroulé du 13 au 15 mars 1989 à Saskatoon, en Saskatchewan. Vingt-sept articles y ont été présentés et portaient sur le rôle de la modélisation forestière, les activités antérieures et actuelles de modélisation, les nouvelles tendances en matière de modélisation et les activités de modélisation dans d'autres secteurs liés aux ressources.

CONTENTS

Page

SESSION I: SETTING THE STAGE

Welcome—A.D. Kiil 2

Introductory Comments—A. Appleby 5

Keynote Address: Modeling the Sustainability of Forest Production and Yield for a Changing and Uncertain Future—J.P. Kimmins 6

A Modeling Primer—R.T. Morton 18

Luncheon Address: Managing Saskatchewan's Forests—Hon. Colin Maxwell 21

SESSION II: PAST AND CURRENT MODELING ACTIVITIES

Computer Modeling Requirements in Manitoba Forestry—R.H. Lamont 24

The Saskatchewan Timber Supply Model: New Directions—J. Benson 27

What I Want in a Computer Model—K.C. Deschamps 33

An Industrial Harvest Scheduling System—N.A. Stevens, W.R. Dempster, and R.M. Watson 38

Question and Answer Session 48

Artificial Intelligence for Forest Pest Management—W.J.A. Volney 50

Wood Quality in Modeling Stand Investment and Harvesting Decisions—R.E. Pulkki 55

The FORCYTE Experience: A Decade of Model Development—J.P. Kimmins, K.A. Scoullar, M.J. Apps, and W.A. Kurz 60

Timber Supply Analysis in the Alberta Forest Service—D.A. Price and E.M. Wrangler 68

Question and Answer Session 85

SESSION III: NEW DIRECTIONS IN MODELING

New Directions in National Timber Supply Modeling—K.L. Runyon 88

A Framework for Analyzing Silviculture Programs—C.V. Pearce, T. McDaniels, and C. Swoveland 89

Practical Applications in Forest Management Planning—D.J. Depta and M.A. Brathovde 96

Integrated Forest Operation Planning—E.W. Robak 104

GIS and Wood Supply Analysis—W.H. Lougheed 110

Question and Answer Session 116

SESSION IV: MODELING IN OTHER RESOURCE SECTORS

Using Hydrological Modeling in Forestry—P.Y. Bernier 120

Habitat Modeling in the Wildlife Sector—J.L. Kansas and R.M. Raine 128

Improving Forest Management in New Brunswick: The Use of Technological Tools—T. Erdle 135

Question and Answer Session 147

Applications of Modeling in Agriculture Production—K.K. Klein 148

Using Climatic Change Scenarios to Model Agroclimatic and Ecoclimatic Consequences—E.E. Wheaton 156

Page

Question and Answer Session 166

Symposium Summary—J.A. Beck 168

Closing Remarks—V.C. Begrand 169

Speakers and Participants 170

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The exclusion of certain manufactured products does not necessarily imply disapproval nor does the mention of other products necessarily imply endorsement by Forestry Canada.

SESSION I:

SETTING THE STAGE

WELCOME

A.D. Kiil
Regional Director General
Forestry Canada
Edmonton, Alberta

Good morning, ladies and gentlemen, and welcome to the "Forest Modeling Symposium." My name is Dave Kiil, and I am pleased to serve as the moderator of this morning's session, entitled "Setting the Stage."

It is gratifying to see such a good turnout, and I am confident that you will enjoy and benefit from the proceedings over the next 2 days. I understand that we have delegates from several provinces and states, including Nova Scotia and Alaska. A special welcome to you all!

In ancient Greece, a symposium consisted of entertainment characterized by drinking, music, and intellectual discussion of some particular subject. I am not sure if we will be able to deliver these activities in quite the same order, but I know that Steve Price, our Symposium Coordinator, has not ignored the ancient formula for success! More on this later.

During the next 2 days we can look forward to an excellent program involving presentations on a wide variety of modeling topics. I will be introducing this morning's speakers in a few minutes, but first I'll give a few helpful comments and observations about how this conference fits into the central theme of change adapted for this series of symposia.

This is the third in a series of symposia coordinated by Forestry Canada (previously the Canadian Forestry Service) and sponsored by federal-provincial forest resource development agreements in the three prairie provinces. Two years ago we convened a conference on geographic information systems (GIS) in Winnipeg and focused on hardware and software availability and applications in forest resource management. Last year's symposium, entitled "Management and utilization of northern mixedwoods," was held in Edmonton and tackled various mixedwood management issues and challenges facing policy-makers, practitioners, and researchers in the years ahead.

Conferences of this type, involving researchers and practitioners, serve as barometers of change. They provide guidance and feedback on research needs and priorities relative to current and future forest resource management issues and challenges. Shortly after the Winnipeg conference, the Northern Forestry Centre established a new research and development (R & D) project entitled "GIS, forest site, and remote sensing." Last year's symposium on management and utilization of northern mixedwoods served as a catalyst for the planning and establishment of a major multidisciplinary project on the management and utilization of mixedwoods and hardwoods.

As mentioned earlier, the central unifying theme of this symposium is change, or rather the speed of change, in forest resource management. More particularly, we will be looking at developments in modeling of forest ecosystems and management activities and, more importantly, at the potential and actual applications of these decision-aid tools.

Now change in the world around us leads to, or at least implies, innovation, i.e., change in the way we do things. It is significant that this afternoon's program commences with presentations by managers and practitioners that address the question: "What I want in a computer model." This should help to pinpoint real or perceived differences in approaches between modelers and those who use and pay for the information generated.

Models of forest ecosystems and forest management systems are certainly not new, but examples of practical applications are just now coming to the forefront. Although nearly one-half of the presentations at this symposium appear to be heavily applications-oriented, many forest-sector decision-makers and practitioners remain to be convinced of the real benefits of models. If we categorize innovators as proactive (10%), dreamers (10%), reactive (50%), and passive (30%), we might then conclude that decision-aid models are gaining acceptability by the so-called reactive part of the population.

At this point, you may well ask why models have not been more widely accepted and applied as decision-aid tools in support of various resource management activities. From my perspective as a manager of R & D, I would argue that the four key determinants of model acceptance by customers are (1) goal-setting, (2) technology transfer, (3) employee education and training, and (4) integrated resource management.

Mention of goal-setting brings to mind a statement in the 1988 report of the federal auditor-general: "I believe it was Martin Luther who said that all human history is like an intoxicated man riding home from a tavern. In his inebriated state, he leans too far in one direction—and falls off the right-hand side of his horse. Determined not to make the same mistake again, he continues his journey leaning to the left, and falls off that side. Thus tumbling off alternately to right and left he somehow makes it home. So with history, we move from one extreme to its opposite."

The auditor-general used this parable to make a point about the lack of consistency in collecting taxes, but the comment about "tumbling off alternately to right and left" helps make a case for goal-setting aimed at determining the desired function of decision-aid models and expert systems. To put it another way, models are gaining acceptance, but perhaps more emphasis on goal-setting by both producer (researcher) and customer (client) would speed up progress!

Another important element of innovation is technology transfer—the two-way communication process between researcher and customer—and ultimately, the packaging of the research product in response to the unique needs of individual customers. Recently I had reason to consider several conceptual models describing the technology transfer process and concluded that problem solving is optimized where the technology resource (researcher) and technology user (practitioner) have well-established links to communicate problem as well as solution messages, each reinforced by strong feedback. This is especially important where research and operations are in different organizations, which is often the case in Canada.

The linking of researcher and practitioner through a mutually agreed-upon technology transfer (communications) network that is directed at well-defined goals can go a long way toward customizing the research product to satisfy the needs of individual customers. Some level of customer involvement in R & D design and subsequent monitoring (as opposed to direct participation in R & D) is highly desirable and more often than not will help build a dynamic working relationship with "downstream" benefits for both. In a way, this approach can be compared to marriage by "looking in the same direction together, rather than looking at each other."

In high-tech applications, technology transfer is being facilitated by the marriage of telecommunications and computer technologies. This trend toward simplification of technologies for everyone's benefit should ensure that the full potential of models, linked to geographically referenced data basis, can be realized.

The education and training of staff to familiarize them with the benefits of using forest models and similar hi-tech tools is essential. I read recently that knowledge doubles every 10 years, suggesting that employees need to reeducate themselves at least three to four times during their careers.

Computer-assisted systems and decision-aid tools can be especially useful in support of multiple-use applications involving different uses of the same land base. Gordon Baskerville touched on this potential in a presentation to the Standing Committee on the Environment and Forestry recently, when he said that "there exists an opportunity to manage a forest for target timber conditions, and for target habitat conditions, both measured in amount and quality, and reached by actively using a variety of tools." The tools would presumably include the application of computer-assisted GIS, linked to ecological and management models, and expert opinion.

Resource management issues are becoming increasingly complex. Rather than manage for one use while constraining or ignoring others, the challenge will be to try to manage for two or more attributes or values. Models and expert systems can help in assessing alternate scenarios and to produce probability statements about outcomes. This approach seems especially timely because changing resource management functions are increasingly reflected in government agencies being organized to manage several related resources, such as forests, lands, wildlife, and fisheries. Consideration of environmental impacts of specific management regimes also needs to be factored into the decision-making process.

In wrapping up my introductory comments, I consider the present symposium to be timely and complementary to the central theme of *change* driving the series. Because change, and especially the *speed of change*, implies innovation, I have touched on four factors that impact on this process: (1) the need for goal-setting to provide a focus for the work and to speed up progress, (2) the need to develop effective technology transfer mechanisms between researcher and customer, (3) the importance of training and educating staff about the benefits of applying new approaches and technology, and (4) the trend towards integrated resource management. Current trends suggest that resource managers will be increasingly challenged to manage for two or more resource values, rather than managing for one and ignoring others. Models and expert systems, combined with computers and interactive data bases, are potentially important decision-aid tools in this process.

INTRODUCTORY COMMENTS

A. Appleby
Assistant Deputy Minister
Renewable Resources Division
Saskatchewan Parks, Recreation and Culture
Regina, Saskatchewan

On behalf of the provincial government and specifically Saskatchewan Parks, Recreation and Culture, I welcome you to Saskatoon and this Forest Modeling Symposium. The organizers have arranged an impressive program that I am sure you will find interesting and informing.

As you know, the Canada-Saskatchewan Forest Resource Development Agreement is sponsoring this symposium, which is one in a long list of forest projects and accomplishments of the 5-year, $28-million agreement. From silviculture to forest inventory, timber management, and forest protection, almost every area of Saskatchewan forest management has benefited in some way from the current agreement. An achievement of particular interest to this group was the purchase under the agreement of Saskatchewan's geographic information system (GIS), which will be invaluable in future forest modeling. The presence of the Forestry Canada office in Prince Albert is also a direct result of the agreement.

Unfortunately, this historic and valuable agreement expires on March 31, 1989. It is hoped that a new agreement will be negotiated speedily and that the important task of managing Saskatchewan forests will continue to receive the extra priority enjoyed during the term of the first Economic and Research Development Agreement (ERDA).

Saskatchewan is not one of the major players in the national forestry sector (for example, British Columbia alone has an annual production of 75 million m^3 of wood compared to our 3.5 to 4 million). The industry is nevertheless important to Saskatchewan. It forms the economic mainstay of many communities such as Prince Albert, Big River, Glaslyn, and Meadow Lake.

Every year forestry regularly generates goods valued in excess of $300 million in Saskatchewan and creates 2.7 direct jobs with an annual payroll of more than $70 million. Another 5100 Saskatchewan residents are employed in jobs that depend on the forest industry.

The new wealth and employment produced by the forest industry contribute significantly to the high standard of living enjoyed by Saskatchewan residents.

In addition to the economic advantages of timber harvest, Saskatchewan's forests are also valued for their recreation and tourism potential and their wildlife, fisheries, mineral deposits, and clean water.

I hope the interchange of information at this symposium will assist all of you in your efforts to maximize the benefits of all of these forest resource values when you return to your own forestry jurisdictions. In the meantime, have a pleasant stay in Saskatchewan.

Keynote Address:

MODELING THE SUSTAINABILITY OF FOREST PRODUCTION AND YIELD FOR A CHANGING AND UNCERTAIN FUTURE

J.P. Kimmins
University of British Columbia
Vancouver, B.C.

DEDICATION

This paper is dedicated with great respect to the memory of Dr. Peter J. Rennie, who has been an inspiration to those working in long-term site productivity since his pioneering work in the United Kingdom in the early 1950s. 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.

ABSTRACT

The expected growth of the human population to about 11 billion 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 these lands must be demonstrably sustainable if forest management is to help arrest rather than aggravate the continuing deterioration of the global environment. The experience-based models traditionally used by foresters cannot predict future forest growth and yield accurately for the altered growing conditions that are expected to accompany the population increase. Knowledge-based, process simulation stand growth models are the only way of predicting future forest growth on a particular site in the absence of accurate data on the past growth of forests on that site. Because they have either been too simple or, if sufficiently complex, have had unacceptably large calibration data requirements that have limited their portability, they have been restricted to research and educational applications. An alternative approach combines "historical bioassay" and process-based modeling approaches into "hybrid simulation" stand models that can provide a way to rank the most probable outcomes and the sustainability of alternative stand-level management strategies under anticipated growing conditions. As the world experiences increasing problems of air pollution, 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.

INTRODUCTION

The single most important factor affecting the future of the world's forests is the continuing growth of the human population, to an anticipated level of about 11 billion (World Bank 1984; Reppetto 1987; Brown et al. 1988). This doubling of the present population is expected to occur within the time necessary for coniferous crops planted on most Canadian clear-cuts in 1989 to reach harvestable condition. Human population growth will lead to a reduction in the area of forest and an increase in demand from the remaining forest for timber products (Council on Environmental Quality 1980; Industrial Working Party 1982; Ford 1983), renewable biomass fuels, chemical feed stocks, clean water, water storage, transportation and power-transmission corridors, recreational experiences, and wilderness and wildlife values. 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, it is expected that air pollution will 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; Bolin et al. 1986; Bell 1986; Morrison 1983, 1984; Binkley et al. 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 although 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 United Nations 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 an IUFRO (International Union of Forestry Research Organizations) Working Group meeting 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 objectives of this paper are to show that currently used traditional stand-level forest growth and yield models are inappropriate tools for assessing the stand-level sustainability of current forest practices in most areas of the world and to propose an alternative stand-level growth and yield modeling strategy. More complete documentation of 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 that constrain our attempts to improve this knowledge. Yield tables, and the yield equations or mensurational models based thereon, are implicitly ecosystem-level models, because the historical record of stand development and biomass accumulation integrates the sum 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 existed during the rotation on which the model was based (Fig. 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 could be unreliable (Ebermeyer 1976; 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. Since that time, yield declines as a result of inappropriate management practices have been reported elsewhere (e.g., second-rotation yield declines in radiata pine in south Australia (Keeves 1966; Squire et al. 1979; 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

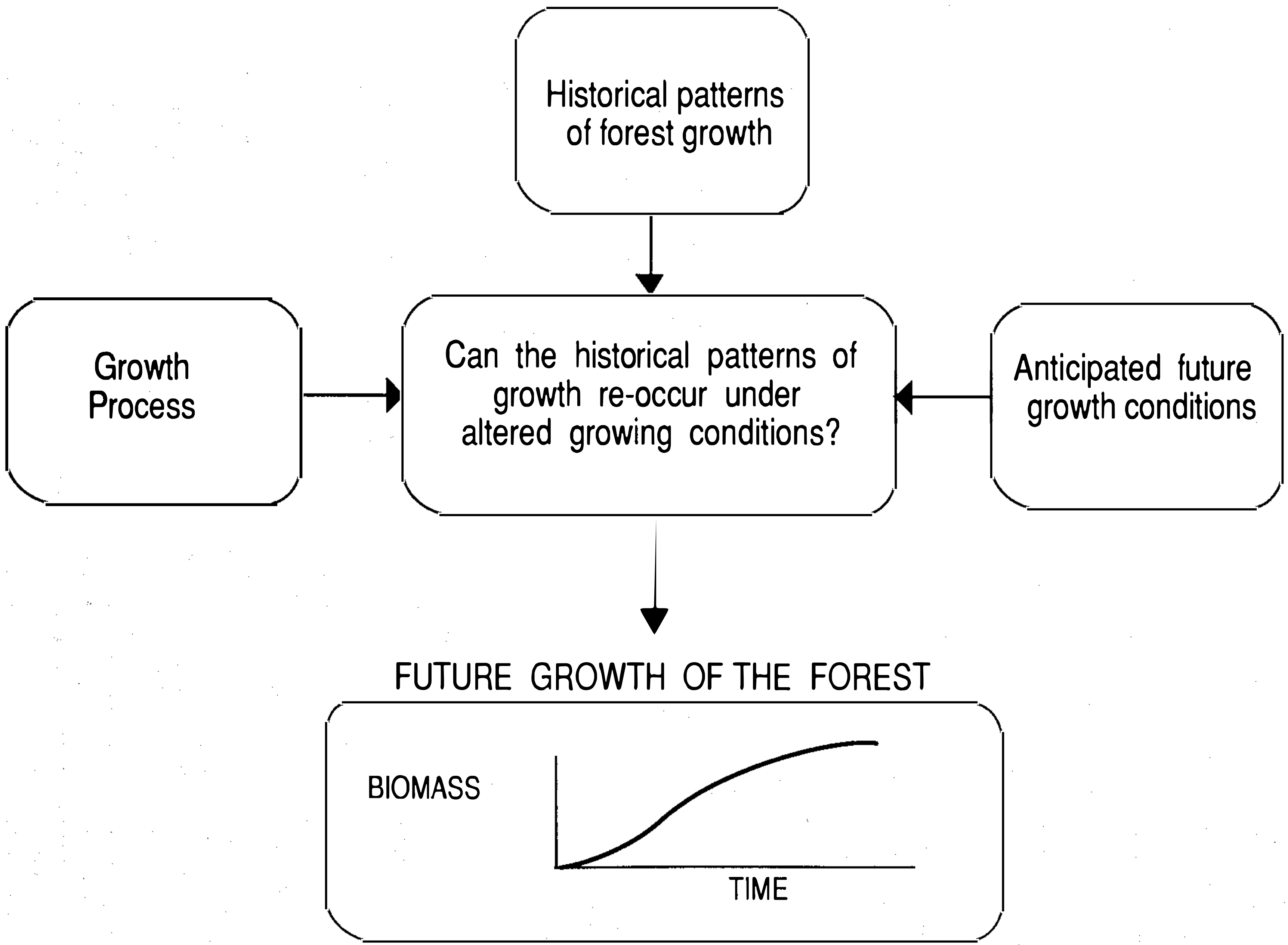

Figure 1. The historical bioassay approach to yield forecasting.

unsuitable as a basis for yield prediction if the future is significantly different from the past, its undeniable value for unchanging conditions notwithstanding.

The evaluation of traditional approaches to forest growth and yield thus depends on whether or not one believes that 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) provide persuasive evidence that climates will be altered significantly within the next rotation of northern conifers. Although there is still great uncertainty about these long-term climate predictions at a regional level, there appears to be a broad degree of unanimity among climatologists that the average world temperature will increase between 1.5 and 4.5°C, that the effects will be much greater at higher latitudes (especially in the nortbern 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 improved growth, while some southern forests may be displaced by grassland. Species requiring winter chilling may be lost in southern or coastal areas.

In addition to climate change, the apparent trend toward 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 susceptibility to erosion, soil biology, and soil moisture and nutrient holding capacity. 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 (Keeney 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 documents growth losses (e.g., Lundmark 1977, 1983, 1986; Anderson 1984; Squire 1983). There is 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 tbe forest regions of Canada (Mahendrappa et al. 1986). Combined with the principles of forest tree nutrition (Ingestad 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; Agren 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 1983b; Gordon 1982; Gordon et al. 1982) but that the attainment of this potential is normally limited by inadequate nutrition (Axelsson 1983a, 1985).

Soil degradation can cause growth losses at the regional level by reducing the area available for forest growth and 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. It is clear that 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.

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 tbe 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 (Nambiar and Zed 1980; Squire 1983), resulting in delays or reductions in crop tree development due to competition, allelopathy, physical interference, or the alteration of the 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). 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 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. Short-term silvicultural responses are relatively uninteresting in Canadian forestry, however. It is the consequences of our management actions and silvicultural investments over the entire rotation that is of major importance (e.g., Lundmark 1977; Kimmins 1986). Considering the changes in forest management that I would anticipate over the next 30-50 years (half of a rotation: see Table 1) and the predicted climatic changes, 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 thabecomes stored as economically harvestable production (i.e., yield) (Fig. 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

Table 1. Canadian forest management in the future

Possible changes	Possible consequences[1]
Shorter rotations Intermediate harvests (thinnings) More-complete biomass utilization Slash and, in some cases, litter utilization	Depletion of soil organic and nutrients
Greater mechanization	Soil compaction and erosion
Greater control of noncrop vegetation	Loss of species diversity and disruption of successional processes of soil and site recovery
Wider spacing and pruning	Increased competition from noncrop vegetation
Greater use of N-fixing species	Improved site N status and greater diversity of weed species
Greater use of nurse crops, alternating crops, and species mixtures	Altered soil fertility and nutrient cycling
Increased use of fertilization and use of forest as a living filter to recycle urban waste (sewage sludge and processed domestic garbage)	Improved soil fertility and organic matter

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

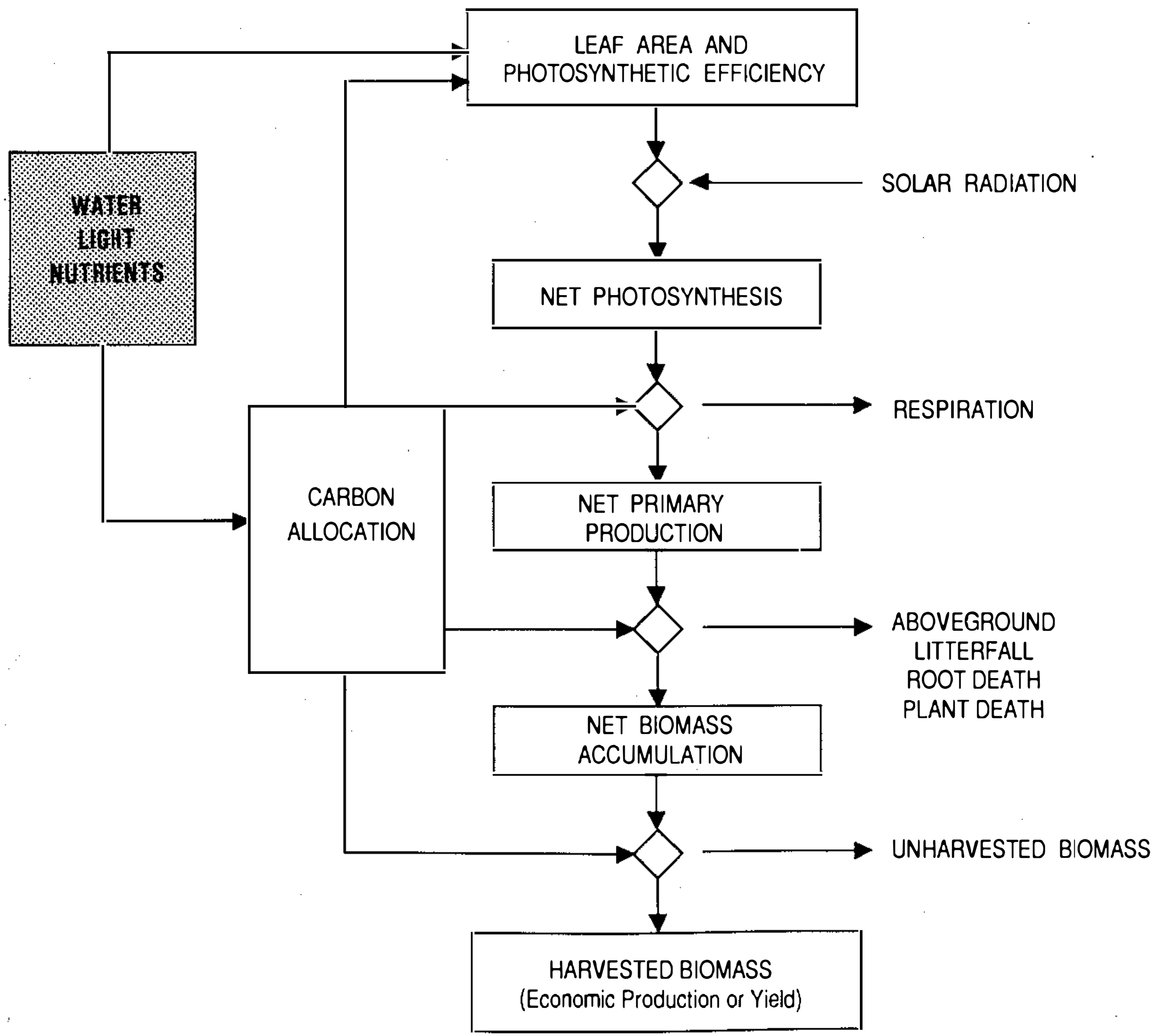

Figure 2. The major determinants of economic production (yield) in a forest ecosystem within a particular climatic regime. Clearly, the availability of site resources (water, light, nutrients) are critically important, both directly and indirectly through their effect on the allocation of net photosynthates.

with input data on the expected future values of these yield determinants, and running the model on a computer (Fig. 3).

Theoretically, this is an ideal approach to the prediction of forest growth and yield because it has the flexibility 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 limited such models to an educational and research role. In most cases, process-based models of forest growth have lacked one or more major determinants of growth. The reasons for this include inadequate scientific understanding of the processes involved, a lack of knowledge about a known process by the individual developing the model, incomplete data for calibrating 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.

There is a growing 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. For the foreseeable future, however, the practical application of process-based models will probably be limited by their heavy calibration data demands, which limit their portability. This limitation has led to the development of a third approach to the prediction of future forest growth: hybrid simulation modeling.

HYBRID SIMULATION MODELING OF FOREST GROWTH AND YIELD

The flexibility 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 (Fig. 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 (Fig. 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 rotation.

This first and best-known example of this approach is the JABOWA series of models, developed initially by Botkin et al. (1972) and elaborated by 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). Models in the JOBOWA 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 extremely successful for this purpose. These models have also demonstrated their value for use in predicting the effect of climatic change on forest composition and succession (Solomon and West 1987; Pastor and Post 1988), and there have been efforts, 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).

For multi-tree species, unmanaged forests in which minor vegetation (i.e., the understory) does not play a significant ecological role in determining site productivity, the JABOWA series has much to offer. These gap models use a variety of growth modifiers (the number and type of modifier varies between the different models in the series) to alter the historical pattern of growth of trees regenerating naturally in small gaps created by the death of individual trees. The modifiers are calculated from input data or are simulated dynamically within a model run. There is some concern (Shugart 1984) that the model's simulation of the response of the vegetation to large-scale disturbance (fire, insects, clear-cutting) 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 clear-cut in 50-ha patches may differ significantly from

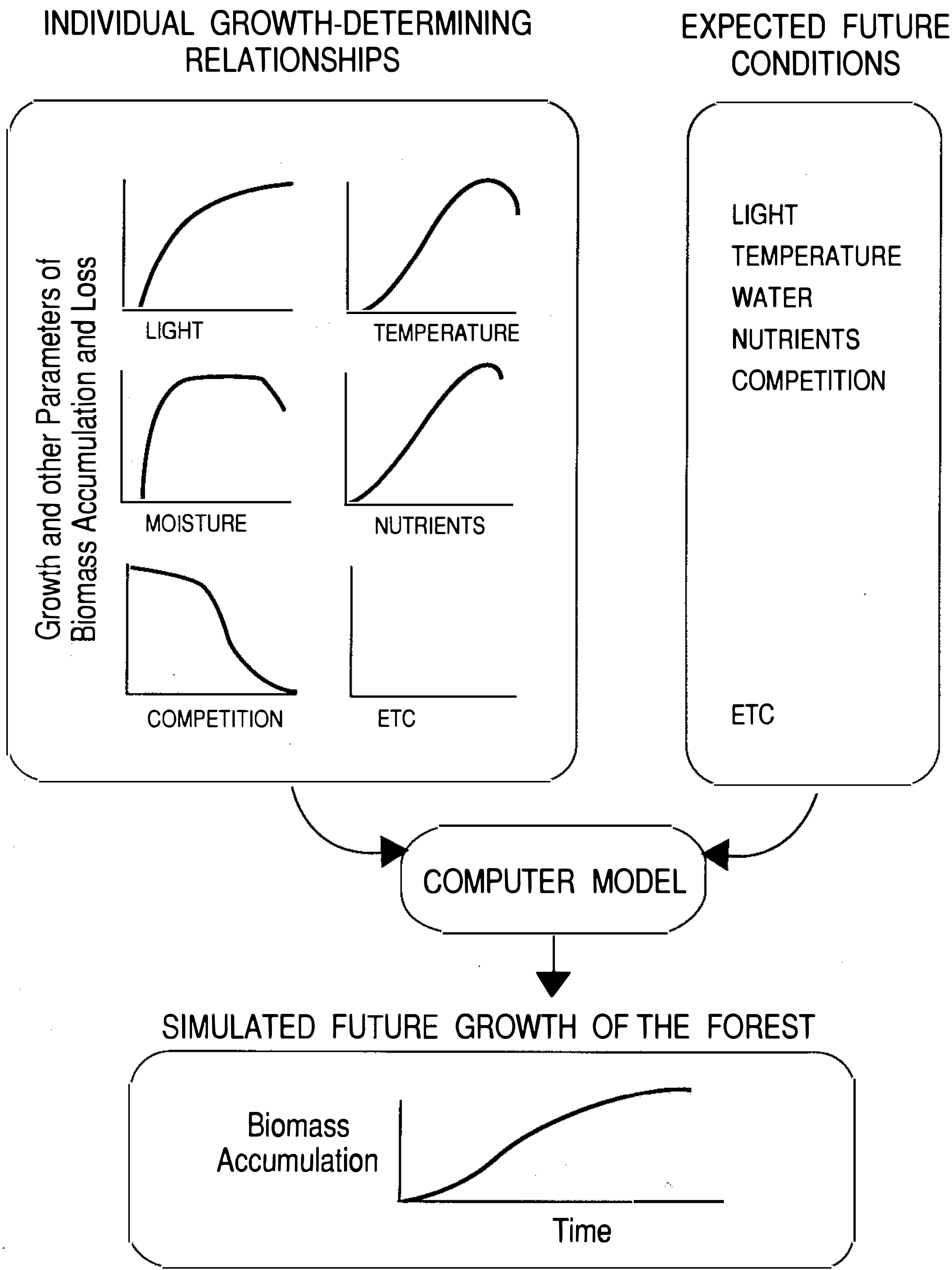

Figure 3. The process-based simulation approach to growth and yield prediction. This is a knowledge-based approach with the flexibility to make accurate predictions for changed future growing conditions.

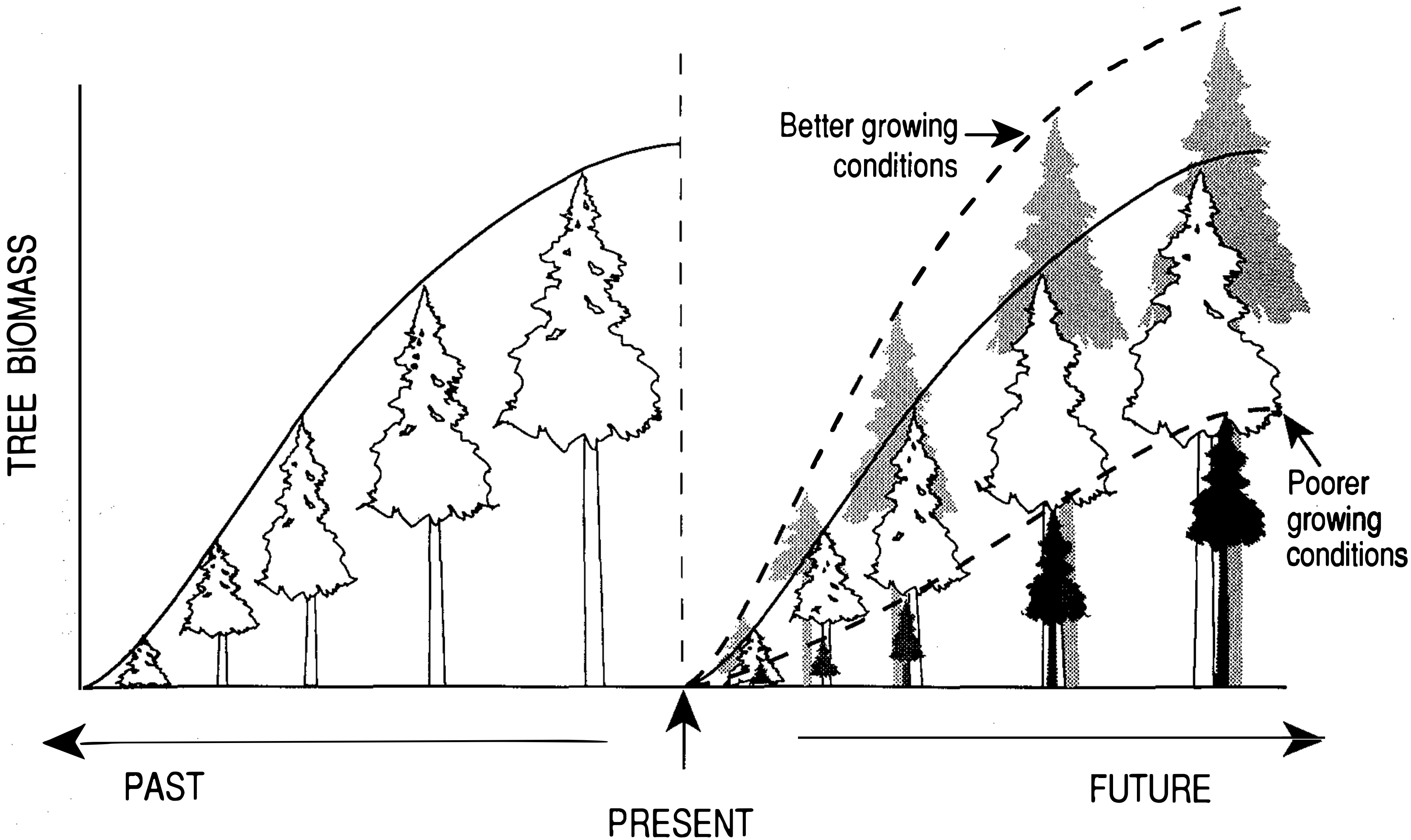

Figure 4. The hybrid simulation approach to growth and yield forecasting. This method combines the historical bioassay and process-based simulation approaches and takes advantage of the merits of both component approaches.

succession in an unmanaged forest, the JABOWA series models will 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, for example, ZELIG[1] (Smith and Urban 1988) should overcome several of these shortcomings.

As the JABOWA series of gap models was being developed by U.S. forest ecologists, the need for a more management-oriented hybrid growth and yield model led to the development of FORCYTE in Canada (Kimmins 1988; Kimmins and Scoullar 1979, 1981, 1983, 1990). The genesis of this development was the ENFOR (ENergy from the FORest) program developed jointly by Forestry Canada and Energy, Mines and Resources Canada. 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 of forest ecosystem function. The result was a hybrid simulation forest ecosystem management modeling framework that has proven to be applicable in a variety of forestry and agroforestry situations around the world.

The FORCYTE models have several capabilities that are not yet available in the JABOWA series. Conversely, the JABOWA-derived models have some abilities that have not yet been added to the latest FORCYTE version (FORCYTE-11). The choice of which type of model to use will therefore depend on the particular objectives of the model user.

The structure and capabilities of the FORCYTE series will not be described here. Details can be found in Kimmins (1986, 1988), Kimmins and Sollins (1989), and Kimmins and Scoullar (1990).

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 favor 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.

ACKNOWLEDGMENTS

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A MODELING PRIMER

R.T. Morton
Silvacom Ltd.
Edmonton, Alberta

INTRODUCTION

Models consist of one or more mathematical expressions designed to represent the processes of a physical system. Modelers and end-users must understand how models are constructed in order to determine a) where and when they should be used, and b) their limitations. This presentation will set forth the ABCs of modeling and will address the following questions:

What is a model?
What are the advantages and disadvantages of models?
When is a model appropriate?
What are the steps in model development?
How do you assess the performance of a model?

WHAT IS A MODEL?

A model is an abstraction of reality designed to represent a physical system. By definition, a system is a connected set of parts that contributes to a complex whole, operating under some principles of procedure. In other words, it is a collection of inputs and outputs, components of which interact under some given rules of operation. Examples of systems include the downstream flow of water creating patterns of erosion and deposition; the rate of spread of forest fires; and growth of individual trees and forest stands.

In most cases we have an incomplete understanding of how complex natural systems operate. Many gaps in knowledge exist. Consequently, models must address the essence of the system rather than attempt to reproduce each individual process within the system.

Models can take various forms. Physical models can be constructed to evaluate conceptual renderings of new buildings or parks or to test the design and performance of bridges, airplane wings, or ships' hulls. Symbolic models include computer program flow charts, organizational diagrams, and construction blueprints. Mathematical models describe the physical system using a set of mathematical expressions. Systems of equations may be solved to provide optimum solutions to management questions or used to simulate change over time. In all cases, models are designed to answer questions about system function without duplicating or replacing every component within the system. As such, models are more cost-effective than building pilot plants or conducting operational tests.

ADVANTAGES OF MODELS

Models provide many benefits. Their primary advantage is their ability to examine system response under varying conditions. For instance, the velocity of water flow can be studied using a physical landscape model or can be simulated with a mathematical model such as Chezy's formula:

$$u = C(RS)^{.5}$$

where u is water velocity; C is the boundary/channel resistance factor; R is hydraulic radius (ratio of cross-sectional area of flowing water to wetted perimeter); and S is the energy gradient, approximated by the slope of the water surface.

Knowing that velocity is proportional to the "smoothness" of the boundaries and the square root of both depth and slope, hydrologists can answer many "what happens if" types of questions. What happens to water velocity if the boundary resistance is reduced through the use of smooth concrete rather than unlined earth channels? What occurs if the hydraulic radius is decreased, the surface slope increased, and the boundary resistance reduced? Answers to these questions can form the basis on which functional systems are designed.

The time frame under which systems respond can often be critical. In contrasts to the first example, the rate and direction of forest fire spread is of immediate concern to those attempting to control a fire. Where a fire is likely to go, and its speed, influence decisions on suppression. Mathematical models, embedded in computer programs, offer a tool to predict fire behavior (in "real-time") as a function of weather, forest stand composition and structure, and terrain. With better information generated by fire behavior models, fire-fighters can optimize their use of available resources.

In some cases, models are the only way to simulate change over time. Growth and yield models provide good examples of this. While forest managers need an indication of yield at some future date to develop management strategies and harvest schedules, mensurationists must develop such predictions without the use of time travel. Growth and yield models, whether simple whole-stand projection systems such as normal yield tables or complex individual tree models, can be used to generate this information. Although there is uncertainty associated with any growth forecasts, these projections are preferable to the alternatives: no information or erratic guesswork.

Growth and yield models also illustrate how models can be used to conduct sensitivity analyses to examine system responses to varying conditions. For example, growth models can predict the effects on tree survival and yield due to treatments such as varied initial spacing, different levels of release or thinning, and related stand-tending activities (e.g., fertilization).

Finally, there is a very real and significant benefit of modeling in the developmental process itself. Building a model forces the investigator to become completely familiar with the logic of the system under study. Identifying and focusing on the essence of a system is an exercise in common sense and compromise. Also, formulating equations to describe individual processes often reveals where significant gaps in knowledge occur.

STEPS IN MODEL DEVELOPMENT

Modeling efforts in the past have attained varying levels of success. To set the stage for a more serious discussion, I would like to present a tongue-in-cheek description of phases in the modeling process:

1. Wild enthusiasm
2. Slight uncertainty
3. Mild disillusionment
4. Complete and utter confusion
5. Search for the guilty
6. Punishment of the innocent
7. Promotion of nonparticipants

Although it is in its infancy, modeling has actually attained a relatively good track record. It is evident from a review of modeling techniques in various disciplines that successful modelers take a similar approach to model development. While no "cookbook" formula exists, the fundamentals of model-building can be summarized as follows:

1. Approach each question using the scientific method of inquiry, experimentation, and empirical proof.

2. Clearly define objectives and determine model scope, application(s), and limitations. Is it being developed simply to describe a system or must it generate forecasts? What outputs and reports should it produce? How will it be used in an operational context?

3. Use common sense to examine system logic. Become completely familiar with the current knowledge of the system under study.

4. Identify the essence of the system. What is truly important to describe and quantify? Boil down the system into the most important components.

5. Identify where serious gaps in knowledge exist. What are the consequences of incomplete information? Should further studies be undertaken to address pertinent questions?

6. Start with the known facts, even if this means stating things like water runs downhill, forest fires spread where fuel exists, or trees grow over time. Models must be reasonable representations of the physical system and when completed should still conform to our basic understanding of how nature works.

7. Acquire and analyze field or laboratory data.

8. Formulate required subsystems and synthesize results of experiments or field trials. Estimate parameters for component equations using appropriate statistical techniques. Examine the performance of each component separately.

9. Assemble model components within a consistent, integrated framework (typically a computer program).

10. Validate overall model performance through comparisons with an independent data-set.

As in most endeavors, time spent planning and designing a strategy for model development is worthwhile. Modelers often encounter a great deal of "noise" that may obscure or mask real relationships. Again, identifying and concentrating on the essential processes is critical to success. One of the trickiest parts of modeling is to properly define appropriate response variables and see through the fog to formulate reasonable mathematical expressions that encapsulate the system components.

This sounds like a lot of work? It is. But great ideas without proper model formulation and development could result in a project that looks better on paper than in real life.

CHOOSING AND USING A MODEL

It is tempting to simply run a computerized model program without making the effort to become familiar with what's happening inside. Treating a model as a "black box" tends to result in one of the following disparate reactions:

1. Excessive significance is attached to model output generated by the computer program. Results may be accepted on faith rather than on a reasoned understanding of how they were produced.

2. All results are viewed skeptically, and the model's potential is unrealized.

Users often confuse the computer program with the model. In fact, the computer program is simply the environment in which the model is running. The model itself consists of the system of equations or other rules of operation. It is consequently much more important to examine the core logic and "mathematics" of the model than to become overly concerned with the appearance of the computer program.

The following are some suggestions for questioning and evaluating models:

1. Be skeptical and demand proof of model performance.

2. Are you familiar and comfortable with the underlying rationale taken in developing the model? Does the approach make sense?

3. Will the model work within the constraints of your operation? Can information needed to run the model be acquired? Is the resolution of the model sufficient to provide meaningful answers to your questions?

4. For what range of data was the model developed? Is it reasonable to suppose that the same assumptions and inferences can be made when applying the model to your situation?

5. What confidence can you place in model predictions? Examine fit statistics (e.g., r^2, SEE, significance of individual coefficients) and predictive indicators (e.g., PRESS). Look at the graphical analysis of residuals to determine how well model components fit across the range of data. If possible, compare model predictions with an independent data set.

Luncheon Address:

MANAGING SASKATCHEWAN'S FORESTS

Hon. Colin Maxwell, Minister
Saskatchewan Parks, Recreation and Culture
Regina, Saskatchewan

I would like to congratulate the symposium organizers for putting on a first-rate show and for granting me the opportunity to address you during this luncheon. As you are all aware, every forestry jurisdiction across the country is currently grappling with difficult issues of timber supply, and forest modeling is a key player in the process.

In general, Canada's record in renewing its public forest has not been exemplary, and although much progress has been made in recent years, we have a long way to go. There are probably a host of reasons for our situation, but two stand out. First, industry in the past has not felt that their existing tenures on public forest lands were secure enough to justify long-term forest management investments. Secondly, successive governments have, for the most part, been unsuccessful in securing the consistent and stable funding required to support adequate forest management.

The competition for public funding is always fierce.

To deal with forest management in Saskatchewan, the provincial government has gone into full cooperative partnership with the forest industry. Since 1986, comprehensive long-term Forest Management License Agreements (FMLAs) have been negotiated for more than two-thirds of Saskatchewan's commercial forest. These new agreements recognize that wood is not the only valid forest resource and that wood users, who have special rights, should also have special responsibilities. As they cut the wood, users should also accept the responsibility to renew the forest promptly and to pay the associated costs.

Independent reforestation trust funds, managed by the agreement holders, have been established for each agreement area. These funds may be used solely for forest renewal projects. Adequate fee structures, reviewed every 5 years, are in place to maintain the productivity of agreement areas. Although allowances have been made for third-party timber allocations within agreement areas, these smaller operators are required to support renewal and management efforts by contributing to the agreement area fund at the same rate as the license holder.

All license holders are required to produce annual and 5-year operating plans in addition to 20-year management plans for examination by the provincial government. License holders are also encouraged to interact directly with other resource users, and plans are approved only after environmental and other resource-user concerns have been addressed.

The business of managing Saskatchewan's forests has taken a giant step forward with our new Forest Management License Agreement system. Through the FMLA system with its attendant reforestation trust funds, the Saskatchewan government has clearly demonstrated its commitment to reforestation.

In the area of technology, Saskatchewan is forging ahead with a new geographic information system (GIS), including development and acquisition costs worth $1.6 million. In the first year, the transfer of already computerized forest inventory data has resulted in an instant operational payback for the system. Over the next 5 years the GIS is expected to provide major contributions to integrated resource management and forest modeling. In the future, the application of improved forest modeling can only serve to refine Saskatchewan's new partnership with the forest industry for the benefit of all Saskatchewan residents.

SESSION II:

PAST AND CURRENT MODELING ACTIVITIES

COMPUTER MODELING REQUIREMENTS IN MANITOBA FORESTRY

R.H. Lamont
Manitoba Natural Resources
Winnipeg, Manitoba

ABSTRACT

Manitoba maintains a detailed forest inventory data-base defining and quantifying the established standing forest resource. The introduction of geographic information system (GIS) computer technology provides the opportunity to effectively interconnect the computer-stored data base with forest modeling programs designed to estimate the future extent of the forest resource. Of primary interest are models that predict the growth and yield of natural and managed stands considering silvicultural treatment and stand management options; models that evaluate wood supply and demand situations; models that evaluate values at risk and potential losses in relation to forest protection responses; and models that relate to wildlife habitat manipulation and animal carrying capacity.

INTRODUCTION

In 1962, The Manitoba Forest Service set an objective to obtain a province-wide forest inventory incorporating a standardized approach to forest cover classification, forest stand measurement, volume determination, and forest-cover map production at a sufficient level of accuracy to provide for forest management planning and annual allowable harvest level determination. The forest inventory was completed for the Agriculture and Forest Zone of the province in 1986, and a continuing maintenance of inventory program is in place to assure that the data base remains current.

In the early 1970s, the concept of using new and evolving computer technology for forest growth modeling and prediction was under active consideration and development. The computer simulation approach allowed the results of many years of forest research to be incorporated into a model of stand responses to forest management activities. Computer simulation of forest stand conditions over time allowed the potential impact of stand management options available to the forest manager to be evaluated before implementing a decision in the forest.

The computer technology required to implement the developing simulation models was not available to most forest managers, and as a result, there were few opportunities to introduce and use this new approach to support daily decision-making actions.

In 1984, Forestry Canada (then the Canadian Forestry Service) under the Canada-Manitoba Forest Renewal Agreement provided the initial funding to allow the Manitoba Forestry Branch to select, purchase, and put into full operation, a geographic information system (GIS). This action placed state-of-the-art technology for forest resource data management and impact analysis into the hands of Manitoba's forest managers at both the branch office and regional level. A lack of computer technology to operationally implement forest stand models is a rapidly disappearing problem that will be nonexistent for the Manitoba Forestry Branch by the year 1991.

THE PRESENT SITUATION

Manitoba's productive forest land area of 15 million ha supports a merchantable volume of 746 million m^3. Considering the present maturity class distribution and present levels of industrial utilization, the total volume of wood available from Crown land to support the forest industry on a sustained yield basis totals 8 million m^3/yr compared to an estimated annual forest growth of 16 million m^3/yr.

The annual harvest by the established forest industry is approaching 1.8 million m^3/yr, and less than 100 000 m^3 are hardwood species. Indicated demand from the established industries continues to focus on softwood species, but new industries have indicated interest in trembling aspen. Should industrial interest be translated into production facilities, virtually all tbe accessible trembling aspen in tbe province would be committed to industrial production within 5 years.

Changes in demand of this nature have a major impact on resource availability, planning activities, and resulting forest stand management efforts. There is also a requirement for changes in attitude. Most foresters and wildlife managers have difficulty accepting that the trembling aspen weed they have been burning, girdling, herbiciding, and shearing at substantial cost to open areas for softwood establishment or to improve wildlife habitat may be in higher demand than some softwood species in such a short time.

Basic growth information relating to the forest resources of the province is minimal. A similar situation exists concerning the response of natural and managed stands to silvicultural prescriptions. Although permanent sample plots to measure changes in growth are being established, little information is available yet on growth processes associated with our present forest cover types. A significant measured permanent sample plot data base is fortunately available from Forestry Canada, which can give guiding forest management information in selected areas of the province. In general, we are unable to accurately predict growth response to the silvicultural treatments now in use.

The introduction of GIS technology is leading to increased data-base aggregation and to increasing integration between data bases that was previously impossible. Because the available basic information can be assembled within a single system, the forest data base can be connected with forest simulation models (assuming the required information is present) without leaving the confines of the computer.

FOREST MODELING REQUIREMENTS

The forest is a constantly changing entity, incorporating a host of variables on which we try to focus our management activities. Years of experience are required to learn the variables and to learn what to expect if the variables are modified. One might wonder whether it is possible to evaluate fully the available options to either manage the forest well or to manage it out of existence. We no sooner learn a technique when new techniques become available that lead to better results, often at less cost. Given this constant change in the forest resource and our continued improvement in knowledge and technology, the potential of computer simulation to aid our management strategies becomes most apparent.

The growth simulation model is important because it provides the building framework for subsequent, more complex simulation models. Simulating the growth of the forest over time and predicting yields in the future can provide the incremental change in our otherwise essentially static forest inventory information base. Output products obtained from growth simulation models should be flexible and include predicted biomass weight and total and merchantable volume estimates at any stand age for both natural and managed stands on a range of site classes and stand densities. When acceptable results are produced by the models through calibration tests with established permanent and possibly temporary growth sample plots, forest managers can add more components. Silvicultural treatment impacts such as thinning, pruning, fertilizing, and drainage should be integrated to evaluate effects on diameter distributions, growth response, and volumes at future points in time. The number of additional variables that can be added for computer simulation is probably infinite. Expected accuracy levels can be variable initially but will be expected to improve with increased experience and knowledge gained with application. No one expects simulation and prediction to be highly accurate in determining the future of the forest resource.

Models that evaluate the economic aspect of the wood supply are of increasing importance as demand increases for a relatively constant sustainable wood supply and full commitment levels are approached. Models of this nature must consider price of the product, cost of production, accessibility of the wood supply, and volumes that are operable under a host of demand and value situations.

Models relating to the value at risk of the forest resource are required to provide predictions of loss relating to insect and disease outbreaks or evaluation of the value of the forest resource with respect to wildfire suppression response. Basic components of models of this nature are in place, but further development work to integrate them directly to the forest inventory data base is required for impact analysis.

Models that use attributes identified in the forest inventory data base to provide wildlife habitat information are increasingly important for our companion wildlife resource managers. Considerable savings in work and time are possible in wildlife habitat assessment and animal carrying capacity determination if simulation models are developed that integrate the available natural vegetation cover information of forest inventories with known wildlife requirements. The ability to manipulate habitat or measure the response of forest management activities with respect to habitat changes within the computer before a decision is made in critical wildlife areas is no less important to the wildlife manager than the forester.

CONCLUSION

Considerable attention has been given by research foresters and scientists to the development of simulation models using available forest measurement data as a base. Forest managers have developed forest data bases with equal attention. We are now ready to integrate the developed and developing simulation models with the forest estate information, to move forest management in its broadest context another major step forward in the 1990s.

THE SASKATCHEWAN TIMBER SUPPLY MODEL: NEW DIRECTIONS

J. Benson
Saskatchewan Parks, Recreation and Culture
Prince Albert, Saskatchewan

I hope that none of you were too surprised to be invited to Saskatchewan for a symposium on forest modeling! Yes, we do have forests, a number of them, in fact. As seen from a Canadian perspective, much of our forest is in the Boreal Forest Region. In Saskatchewan, the provincial forest, as defined in the Forest Act, amounts to about 650 000 km^2 or about 54% of the total area of the province.

Only about 40% of the provincial forest is considered commercially accessible, however. This commercial forest portion is bounded in the south by agricultural development and in the north by the Clearwater and Churchill river systems. Just over one-half of this area is productive forest land. From a fairly stable amount of commercial harvesting taking place in the early 1960s, the value of forest products rose from about $10 million to more than $100 million in the mid-1970s. Today, with the new Weyerhaeuser paper mill, the value of forest products will approach $500 million.

Prior to 1980, timber supply analysis in Saskatchewan was still somewhat unrefined. There was an apparent surplus of timber and more importantly, a total lack of age data associated with the inventory data base. The analysis tool of record for the calculation of annual allowable cut (AAC) was Von Mantel's formula: AAC = (merchantable volume)/one-half rotation age.

On a province-wide basis, the age class distribution may be sufficiently varied to produce reasonable answers, but regionally there could be problems, when the formula could easily produce significant over- or underestimates of the annual allowable cut.

In the mid-1970s, with the introduction of the metric system, a new cycle of forest inventory was started. As part of this exercise, the commercial forest was stratified into physiographic blocks. The intention was to create a separate data base for each block. In addition,the forest classification system was revised, and a number of new variables were added to the photo interpreter's load. The end result is shown in Figure 1.

Field sampling was based on the forest cover type of the portion of the classification, using a modified 3P system. Today we have more than 24 000 plots established in the commercial forest.

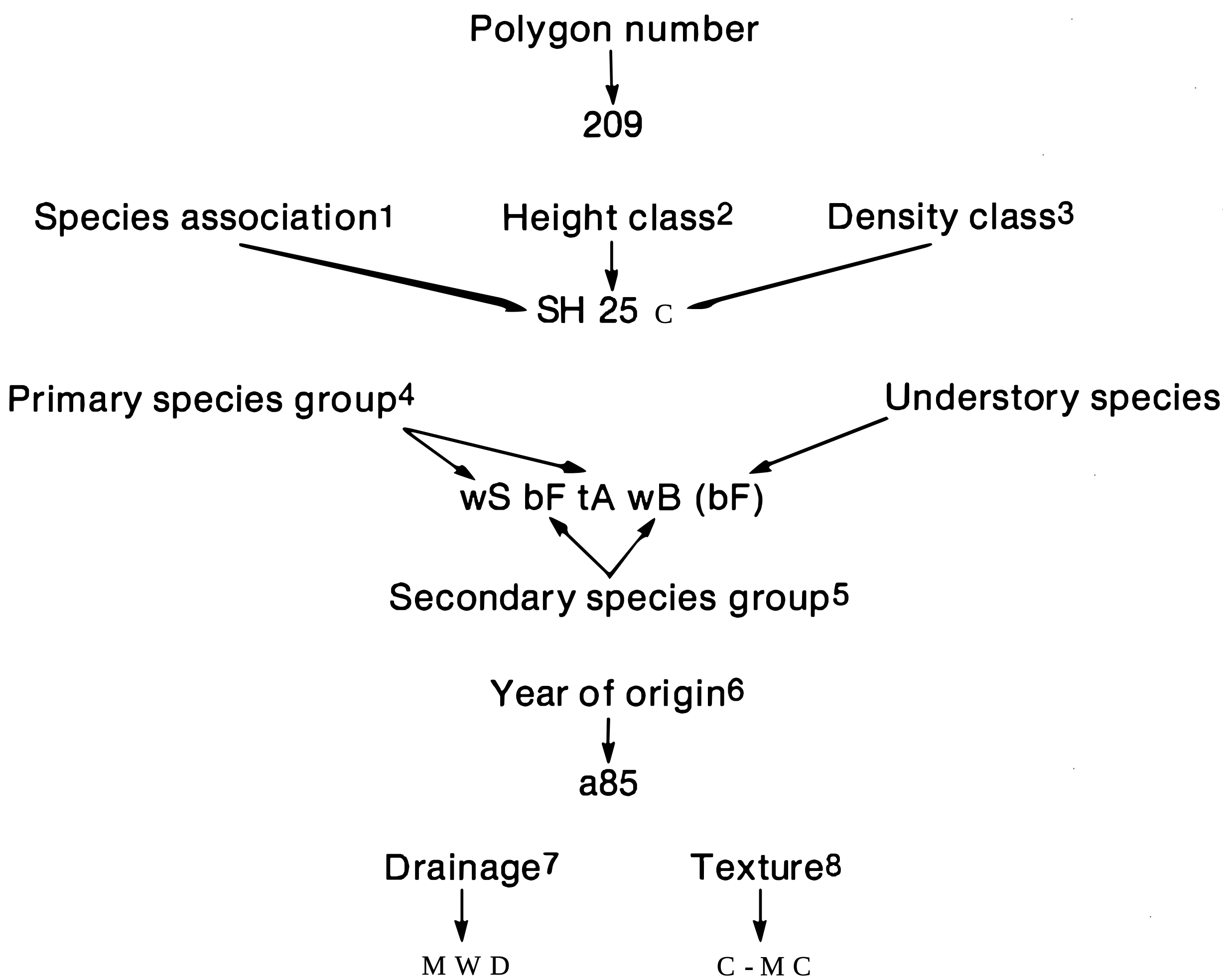
By the early 1980s sufficient data were loaded on computer to allow us to begin a new style of timber supply analysis. With age data on the inventory it was possible to create natural stand yield tables, recalculate rotation ages, and start using fancy supply models. Our first species analyzed was jack pine, and we very quickly discovered that there appeared to be something wrong with the data. The rotation age dropped from the 80 years established from permanent sample plots to 45 years from the actual stand-level information. At about the same time we learned that Alberta was having similar problems and that the probable cause was errors, random or otherwise, in the age-class data.

Our solution to this problem of biased yields was to go back to the published rotation ages that had been developed over the years from analysis of permanent sample plot data. We then compiled the volume and area information in the year of origin classes on and near those rotation ages for each of our so-called growth types. A growth type is an aggregation of height classes, density classes, and in some cases, species associations. An example here would be the jack pine growth type, JPGT. This is a combination of all height and density classes in the S species association, with jack pine as the primary species.

With these yields-at-rotation-age in hand, we were in a position to start calculating new annual allowable cuts.

As part of this process we had a number of very interesting discussions with people like Jim Beck at the University of Alberta and Dick Dempster, now in private consulting. These discussions resulted in several replacements for the term allowable annual cut. Our replacements were as follows:

1. Harvest Volume Schedule (HVS): This is the amount of timber that can be harvested annually



[1] SH = a softwood-hardwood mixture.
[2] The maximum height is 25 m in this case.
[3] C = 55-80%.
[4] wS = white spruce; tA = trembling aspen.
[5] bF = balsam fir; wB = white birch.
[6] Year of origin = age class.
[7] MWD = moderately well drained.
[8] C-MC = coarse to moderately coarse.

Figure 1. Characteristics of Polygon 209 in Saskatchewan's forest classification system.

from the bush you have with all its warts and blemishes.

2. Long-Run Sustainable Yield (LRSY): This will be the available annual harvest, presuming the land base remains forested in the same proportion of growth types and that the yields at rotation age are the same as the present natural forest.

3. Allocated Harvest (AH): This is the volume that is actually allocated for forest harvesting. Generally we would recommend that on the average this amount would be less than or equal to the harvest volume schedule. In a case with an overmature age class distribution, however, the allocated harvest may very well be higher than the harvest volume schedule to avoid losing the timber to such things as mortality or disease. The calculations done for each of these is shown here:

$$\text{HVS} = \frac{(\text{Mature} + \text{Overmature volume}) + (\text{Immature ha} \bullet \text{Yield/ha})}{\text{Rotation}}$$

$$\text{LRSY} = \frac{\text{Total ha} \bullet \text{Yield/ha}}{\text{Rotation}}$$

$$\text{AH} = \text{Demand, generally less than HVS}$$

Most of our current efforts go into the calculation of the HVS for each of our timber supply areas. Table 1 provides an example of this analysis; it shows the actual volumes that are sustainable over the rotation age of each growth type. The histogram (Fig. 2) illustrates the timber volumes as they become available over time. The column on the left is the present mature and overmature volume, and each of the other columns are based on yields as the growth types reach rotation age.

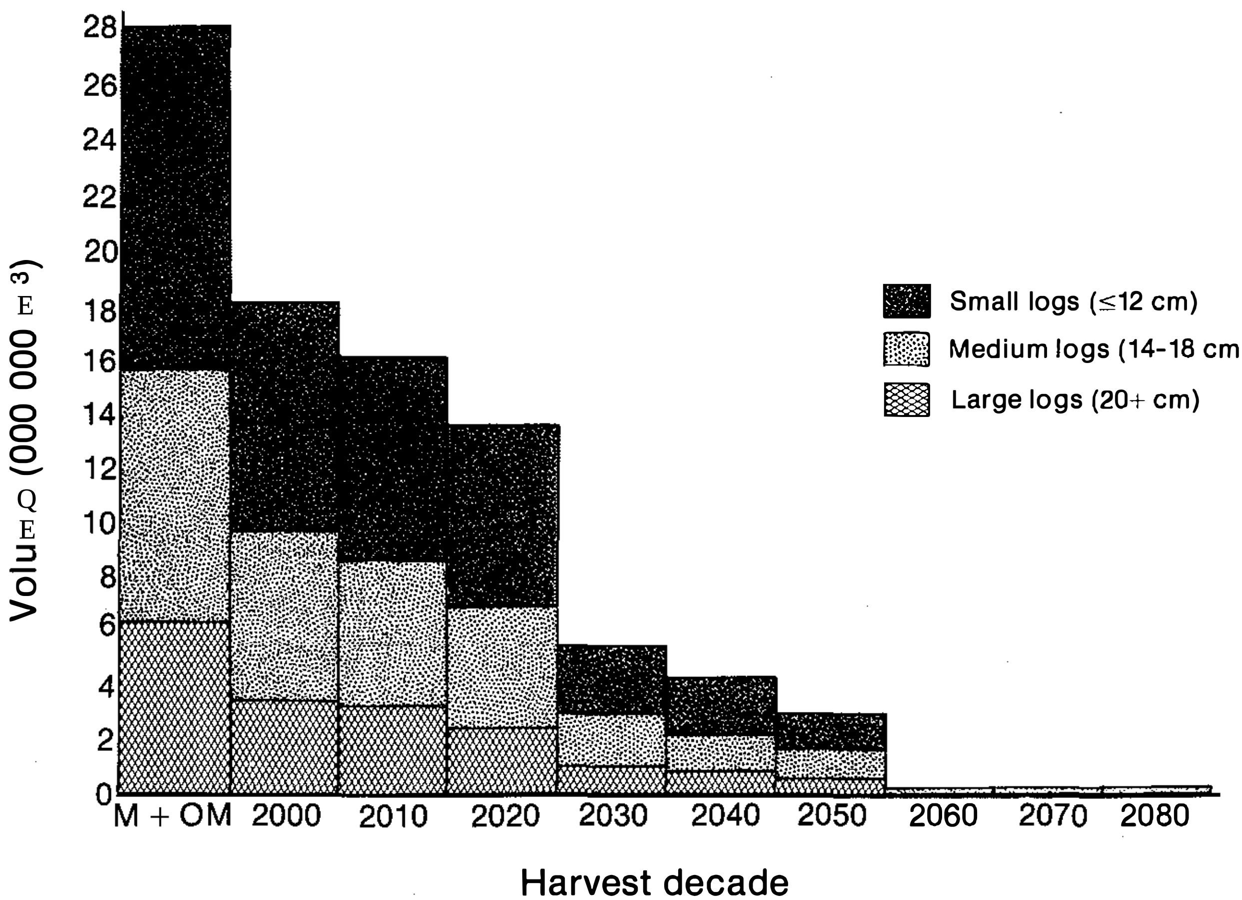


Figure 2. Harvest volume schedule for the Fort a la Corne Provincial Forest (all species in all growth types).

Table 1. Forte à la Corne Forest hardwood harvest volume schedule by species

Growth type	Total area (ha)	Volume (m^3) Large logs (20+ cm)	Medium logs (14-18 cm)	Large and medium logs (14+ cm)	Small logs (≤12 cm)	Total (≤999 cm)
Trembling aspen						
White spruce		439	403	842	410	1 252
Black spruce		71	96	167	89	256
Jack pine		625	931	1 556	1 217	2 773
Spruce/pine		15	19	34	16	50
Pine/aspen		577	808	1 385	1 146	2 531
Tamarack-larch		0	0	0	0	0
Trembling aspen		8 226	12 350	20 576	18 014	38 590
Total		9 953	14 607	24 560	20 892	45 452
Balsam poplar						
White spruce		43	50	93	61	154
Black spruce		19	46	65	65	130
Jack pine		3	46	49	46	95
Spruce/pine		0	1	1	1	2
Pine/aspen		9	19	28	53	81
Tamarack-larch		2	3	5	2	7
Trembling aspen		360	575	935	991	1 926
Total		436	740	1 176	1 219	2 395
White birch						
White spruce		18	51	69	128	197
Black spruce		6	19	25	39	64
Jack pine		1	44	45	132	177
Spruce/pine		0	4	4	5	9
Pine/aspen		31	55	86	126	212
Tamarack-larch		0	9	9	5	14
Trembling aspen		287	631	918	1 609	2 527
Total		343	813	1 156	2 044	3 200
All						
White spruce	3 204	500	504	1 004	599	1 603
Black spruce	7 291	96	161	257	193	450
Jack pine	40 222	629	1 021	1 650	1 395	3 045
Spruce/pine	838	15	24	39	22	61
Pine/aspen	7 065	617	882	1 499	1 325	2 824
Tamarack-larch	2 075	2	12	14	7	21
Trembling aspen	41 530	8 873	13 556	22 429	20 614	43 043
Total	102 225	10 732	16 160	26 892	24 155	51 047

NEW DIRECTIONS

Where do I think we should be going? Well, my wish list is quite long, but I would like to emphasize three things.

First, we must recognize forest value dynamics (Fig. 3). As with timber, the value of other resources and uses associated with the forest changes over time. Our analyses and models will have to be based on a team approach.

Secondly, foresters have always given lip service (but very little else) to the recognition of the statistical error that accumulates from sampling and from mathematical manipulation. If only standard error from sampling is used, it is possible to attach a level of confidence to each timber supply analysis (Table 2). Such information is easily calculated at the growth type level and can be expanded out to the full analysis.

Finally, we must recognize the level of complexity of the data we have on hand today and build our models accordingly. We can always build more-complex models when we develop the more-complex data bases necessary to drive them.

In summary, timber supply analyses must be dynamic. We must recognize forest value dynamics and be prepared to work with our fellow professionals in other disciplines. We must be prepared to identify the mathematical confidence we have in our analyses, and we must not try to stretch our data beyond reliability.

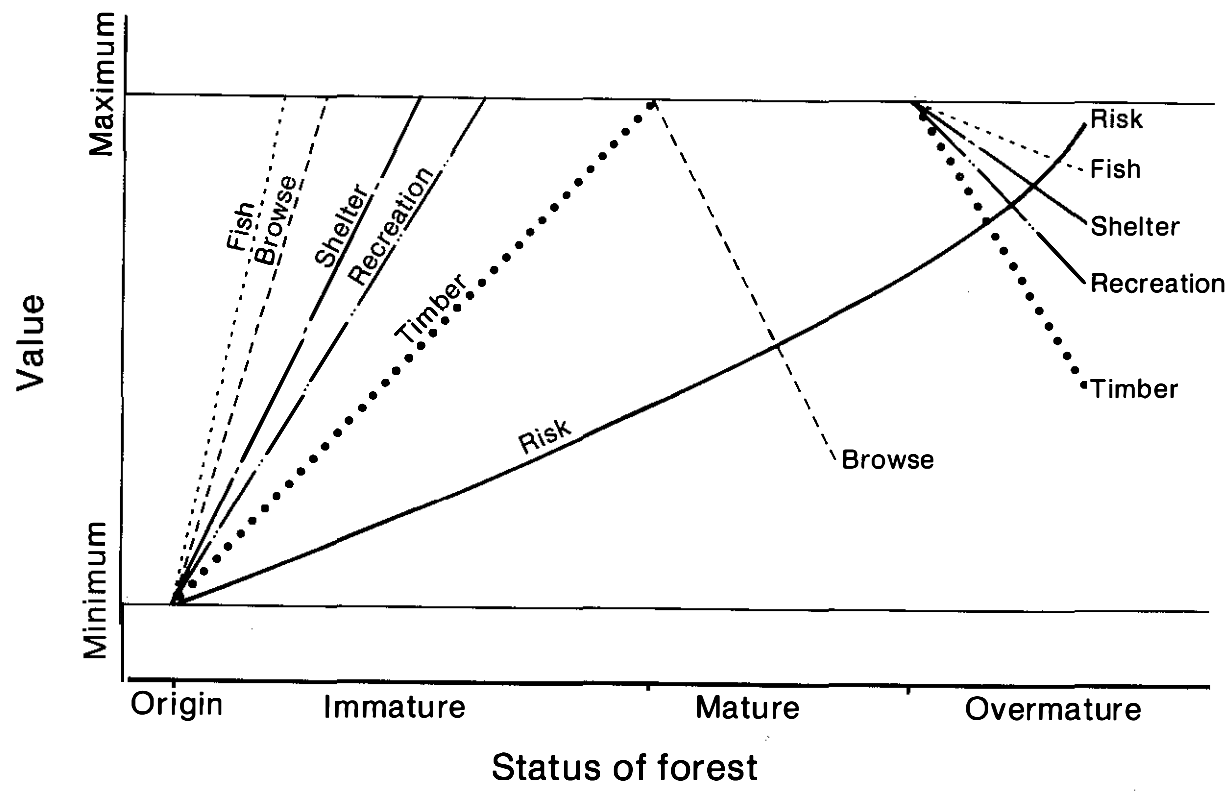


Figure 3. Forest value dynamics.

Table 2. Timber supply confidence levels

Species group[a]	Total samples	Confidence limits[b] (±%)
S—white spruce	760	4.5
SH—spruce[c]	1 100	3.5
HS—spruce	1 216	3.5
Subtotal	3 076	2.4
S—black spruce	851	8.0
S—jack pine	1 091	5.4
SH—jack pine	1 018	6.8
HS—jack pine	812	6.8
Subtotal	2 921	4.3
Total	6 848	2.4

[a] Species groups are differentiated by their softwood content: S is >75%, SH is 50-75%, and HS is 25-50%.
[b] These limits will be exceeded 5 times out of 100 due to sampling error; note that no adjustment has been made for forest growth.
[c] White or black spruce.

WHAT I WANT IN A COMPUTER MODEL

K.C. Deschamps
Alberta Forest Service
Edmonton, Alberta

INTRODUCTION

Alberta is endowed with a rich forest resource of some 35 million ha, which represents about 60% of the total area of the province. This forest, which lies within the Green Area (Fig. 1), is primarily administered by Alberta Forestry, Lands and Wildlife under the three guiding principles of sustained yield, multiple use, and environmental protection. All land within the Green Area is owned by the Government of Alberta.

Forest land in Alberta can be divided into two major regions (Fig. 2). The first region is the Boreal Forest Region, which is made up predominantly of young, fire-origin, mixedwood stands of spruce and aspen. The other major region is the Eastern Slopes Region of the foothills. This region is dominated by fire-origin even-aged stands of lodgepole pine and some small spruce and Douglas-fir stands.

Current estimates of the forest resource (Fig. 3) show that we have 1.51 billion m^3 of coniferous growing stock (47% white spruce, 40% pine, 9% black spruce, and 5% other conifers) and 0.83 billion m^3 of deciduous growing stock (mainly aspen and balsam poplar). This translates to a sustained annual allowable cut (AAC) of 14.5 million m^3 of coniferous (70% committed as of April 1988) and 11.6 million m^3 of deciduous (20% committed as of April 1988). With the several recently announced forestry developments, both the coniferous and deciduous AAC are near or at full commitment. As a result of this increased forestry development and high commitment of the forest resource, the Alberta Forest Service (AFS) is relying more heavily on models to provide the necessary information to wisely manage the forest land base.

COMPUTER MODELS: CURRENT USE AND FUTURE NEED

Historically, computer models have been used by the AFS in the Timber Management Branch for provincial timber supply analysis. A good description of this information is included in a paper by Price and Wrangler in these proceedings. Virtually all of the information used to create these computer growth models has been collected in natural stands.

Within the Reforestation and Reclamation Branch, computer models are primarily used to help with storing, retrieving, manipulating, and analyzing provincial regeneration survey data. Recent requests by Timber Management Branch for silvicultural inputs to the Provincial Forest Management Unit Plans require the use of dynamic computer models to evaluate silvicultural opportunities. Managed-stand yield tables or growth models that project the long-term dynamics of the managed stand are not currently available in Alberta. A computer simulation of responses was therefore chosen as an alternative. The stand model PROGNOSIS (Stage 1973) was used to simulate growth, yield, and financial responses of various silvicultural treatments. With the results, silvicultural opportunities were evaluated, and further modeling was done to determine potential changes to the AAC.

The Reforestation and Reclamation Branch is responsible for the managed stand from regeneration through to scheduling and check-off for harvest. The branch is also responsible for the application of silvicultural treatments, many of which have a profound effect on the future stand development, yield, and financial value.

In this regard, computer models are needed to help with the following:

1. evaluation of the effects of various silvicultural treatments on future stand development, yield, and financial value of managed stands of lodgepole pine, white spruce, and trembling aspen on a variety of site types;
2. identification of appropriate management alternatives for mixedwood stands;
3. identification of lands to be managed intensively versus extensively.

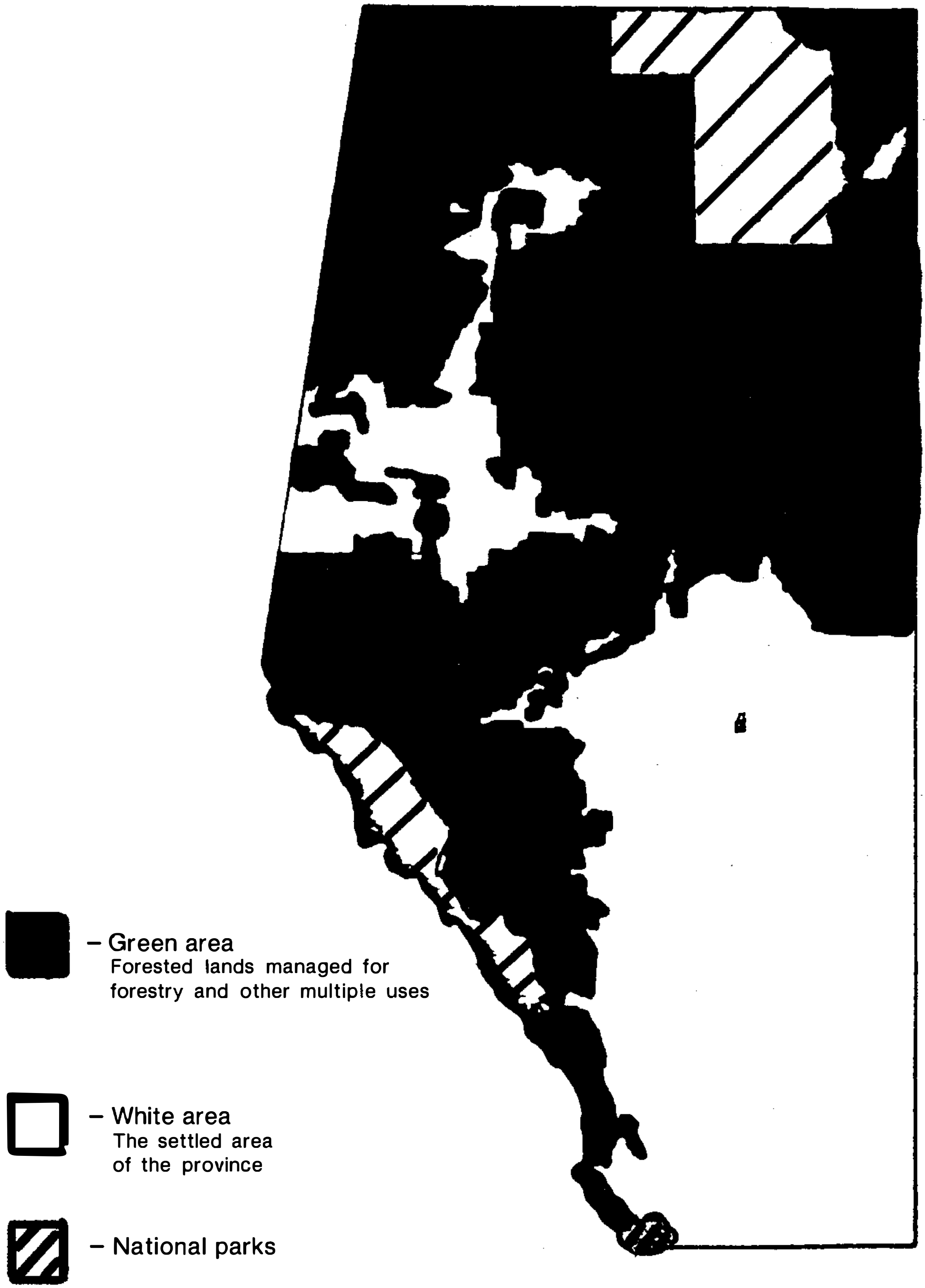


Figure 1. Public lands classification map of Alberta (Alberta Forestry, Lands and Wildlife 1988).

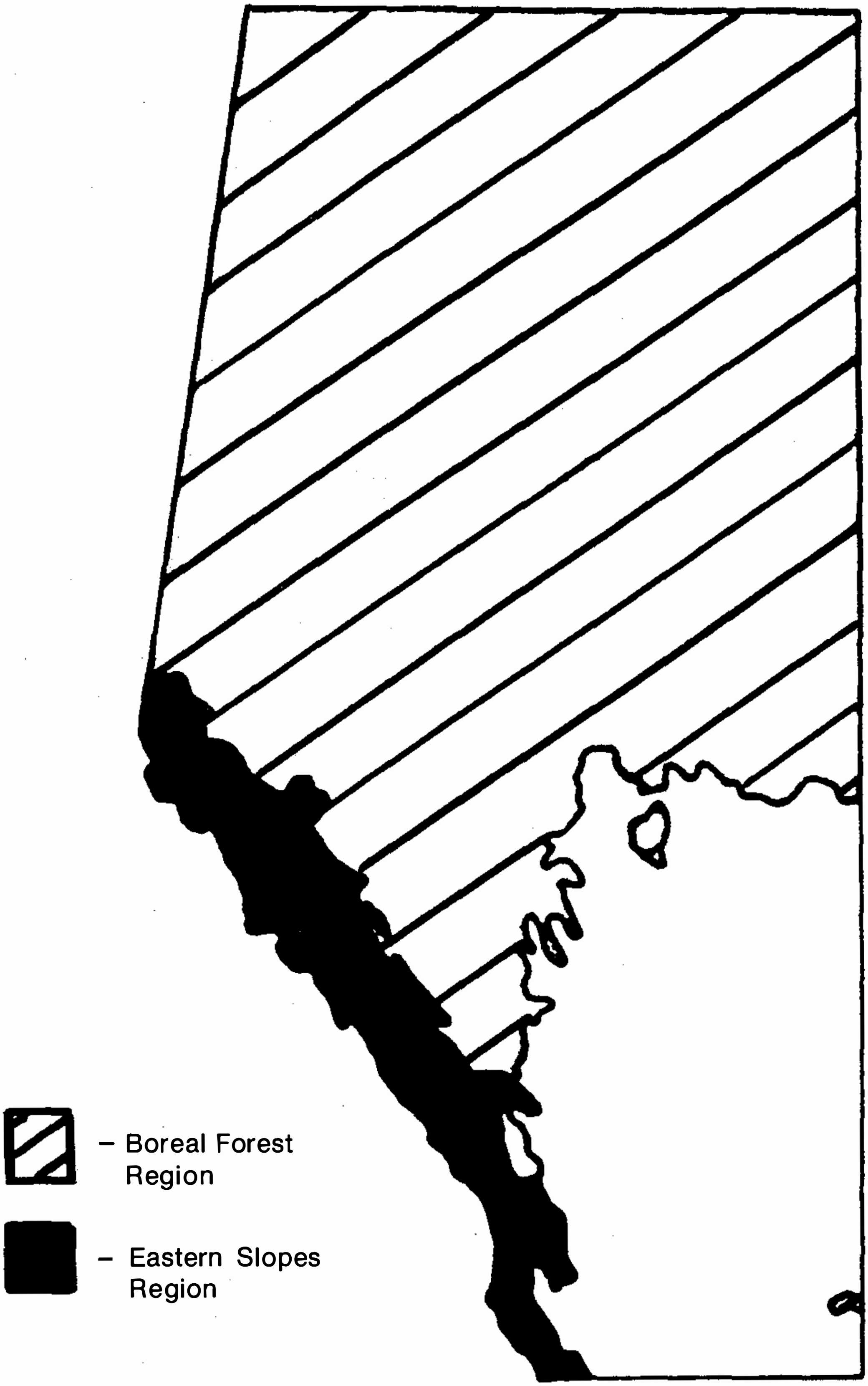


Figure 2. Forest regions of Alberta (Alberta Forestry, Lands and Wildlife 1988).

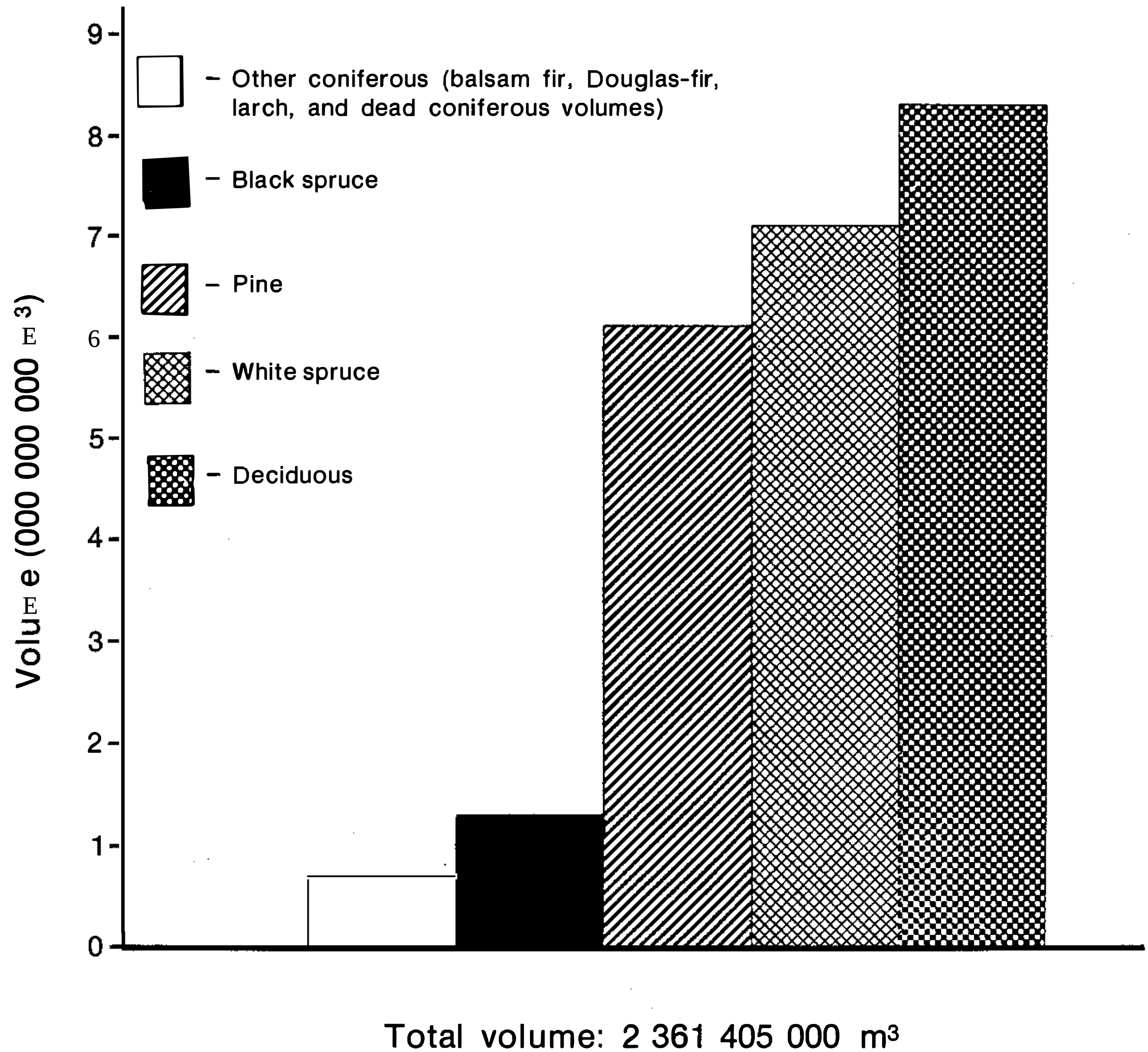


Figure 3. Total provincial timber volumes (Alberta Forestry, Lands and Wildlife 1988).

WHAT WE WANT FROM MODELS

We want simple, flexible, user-friendly predictive growth models that will project the stand development, yield, and financial value of stand management with reasonable accuracy.

The models developed must be easily understood by the users. For the most part, the users are forest managers with limited hands-on modeling experience. If the users require a Ph.D. to understand the model basis, assumptions, or what they do, chances are they will not use the model.

The models developed must be flexible. They should provide estimates of stand development, yield, and financial value starting from freshly harvested areas or from existing conditions, for a variety of sites, species, and silvicultural treatments. Over the long term the models should provide estimates of expected forest changes from insects, disease, weather, and other factors.

The most common problem with models (or modeling systems) is that many are not developed to be very user-friendly. The models must be thoroughly and clearly documented in a language the user can understand. Sample model runs and straightforward user guides should be available. In addition, help menus on the computer should be included and easily accessible. The models developed should be driven by available data. Over the long term, silviculture growth models will have to be incorporated into timber supply analysis. These models must therefore be able to interact with the existing inventory conditions. In addition, the models should be easily calibrated to existing conditions and provide some structure for future data collection. The models developed must have understandable output. They must be both meaningful and useful for the user, not for just the developers.

The models should project the product of silviculture intervention with reasonable accuracy. The models should be constructed to make them as reliable as possible for extrapolation. A model should include extensive information about its performance under a variety of conditions. This information should be in a language easily understood by the user.

Buchman and Shifley (1983) have written a guide to evaluating forest projection systems. In their paper they assembled and organized a set of criteria to assist users in selecting modeling systems. The three criteria they discuss for evaluation are application environment, performance, and design. This would be a good paper to read before selecting a modeling system.

In summary, forest managers are starting to use personal computers for different applications, and they have learned that computer packages must be user friendly and do what they want then to do. Much too often, computer models become the property of the developers rather than the users. Communication is needed between the developers and the users for model needs, assumptions, data, calibration, and output. This can only provide forest managers with better tools for addressing their management needs.

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AN INDUSTRIAL HARVEST SCHEDULING SYSTEM

N.A. Stevens and W.R. Dempster
W.R. Dempster and Associates Ltd.
Edmonton, Alberta

R.M. Watson
Procter & Gamble Cellulose Ltd.
Grande Prairie, Alberta

ABSTRACT

The realistic modeling of forest management requires an accurate but comprehensible representation of the management system and process. A forest-level model is presented that is currently used for harvest scheduling of Procter and Gamble's Forest Management Area in Alberta. The model schedules cut units, which represent groups of stands that can be treated as the same for the purposes of operational sequencing and defining operating conditions and costs. This structure allows for the projection of important operational factors as well as volume. The replanning process used in timber management is also simulated to ensure realistic projection of volume flows.

INTRODUCTION

Most agencies and companies involved in timber management planning formulate a mathematical model of the forest to schedule harvests. The reliability of the harvest calculations depends on the accuracy of the assumptions regarding land area, management practices, and forest characteristics such as productivity and growth response to treatment, as well as the formulation of the harvest scheduling model itself.

The forest inventory is categorized into strata typically consisting of age classes within yield classes. These strata become the units used for scheduling harvests. Limitations with the structure of many forest-level models prohibit the strata from maintaining a geographic identity. The result is that the units used for scheduling harvests with the model are geographically dispersed. Actual harvest patterns are determined by a more complex combination of factors including accessibility, haul and harvesting costs, nontimber values, and market conditions. Because of the failure of most harvest scheduling techniques to model operational considerations, the harvest level determined by such methods may not be possible to achieve. Not surprisingly, the use of such models in actual operational scheduling has been limited in extent and utility, leading to a lack of continuity in the planning process.

Timber management planning is a sequential decision-making process. Plans are updated at periodic intervals to reflect changes in policy, volume projection, and growing stock. With a few exceptions, conventional models for determining harvest levels do not model the planning process used in timber management. The failure to model the replanning process will generally produce misleading volume schedules, and inappropriate policies may be developed on the basis of these schedules.

The purpose of this paper is to present a harvest scheduling model designed to simulate operational harvesting procedures and the sequential planning process. The model is known as the Compartmental Harvesting And Replanning Model (CHARM). A comparison is made between the harvest schedules produced by CHARM and those produced using Timber RAM (Navon 1971) and a traditional area-volume check (Chapelle 1966).

PROCTER & GAMBLE'S FOREST MANAGEMENT SYSTEM

Forest Organization

Procter and Gamble's (P & G) current operations in the Grande Prairie area consist of a kraft pulp mill rated at 300 000 t/yr and a 150 million board-foot dimensional lumber sawmill. Procter and Gamble renewed its Forest Management Agreement (FMA) with the province of Alberta in December, 1988, and under the terms of this renewal agreement the FMA area has doubled in size. The analysis described in this paper, however, is limited to the original FMA area.

Management Areas

The original FMA area encompassed about 1.3 million ha of forested land in the vicinity of Grande Prairie. It was divided into four management areas, and an annual allowable cut (AAC) was calculated for each area. This division was based primarily on operational and administrative needs.

Compartments and Subcompartments

Each management area is divided into cut compartments, which number from 5 in the smallest management area to 22 in the largest. A cut compartment can best be described as a logical operating unit, the boundaries of which are usually well-defined features such as rivers, ridge tops, or roads. The average cut compartment is about 25 000 ha in size. Compartments are divided into subcompartments, which are groups of stands within the compartment that can be treated as the same for the purposes of sequencing operations and defining operating conditions and costs. This recognizes the reality of forest operations; logging, for economic reasons, tends to be concentrated in one area (i.e., a subcompartment) at a given time rather than scattered over an extensive area harvesting on a stand by stand basis. To the south of Grande Prairie are large areas of mature and overmature forest of lodgepole pine and white spruce. Cut compartments in the southern FMA area are therefore usually cut in two passes. Subcompartments in this region represent the area to be cut in either the first or second entry. In the mixedwood boreal forests to the north, cut compartments tend to have a diversity of age classes, and therefore multiple entries into the cut compartments for harvesting are expected. The number of subcompartments per cut compartment in these areas may number six or more.

Information Needs

The following information is what P & G considers important for long term strategic planning.

Under the terms of the FMA, allowable annual cut estimates need to be recalculated every 10 years. An understanding of what future AAC revisions are likely to yield therefore is important in assessing long-term fiber supply security and expansion potential. Also of interest is an understanding of how operational decisions may affect allowable annual cuts; i.e., what is the AAC impact of cutting subcompartments 3.2A before 3.6A; what happens if Management Area 3 is undercut for the first 10 years, etc.

Factors other than volume, however, are also important from a business viewpoint, and a projection of these items over time is required. Listed below are operational factors that Procter and Gamble consider in developing a harvest sequence:

1. volume to be cut by commuter operations;
2. sawlog volume;
3. haul cost;
4. approximate species composition;
5. volume of wood available to summer operations; and
6. capital road and bridge costs.

In summary, Procter and Gamble requires a tool that allows it to understand the operational and fiber supply impacts of logging subcompartments in a particular sequence at a varying rate of cut.

DESCRIPTION OF CHARM

The CHARM model is a microcomputer-based harvest scheduling model. It uses a binary search technique (Johnson and Tedder 1983) to find the maximum even-flow volume that can be sustained over a planning horizon. Because it is a simulation model, the solutions it determines are not necessarily optimal; however, repeating the simulation using alternative configurations can identify suitable solutions.

The model incorporates three features that give it the ability to realistically model operational harvest scheduling:

1. The unit used for scheduling the harvests, the subcompartment, is geographically based. The user can specify the harvesting sequence by subcompartment or alternatively allow the model to harvest the oldest subcompartment first.

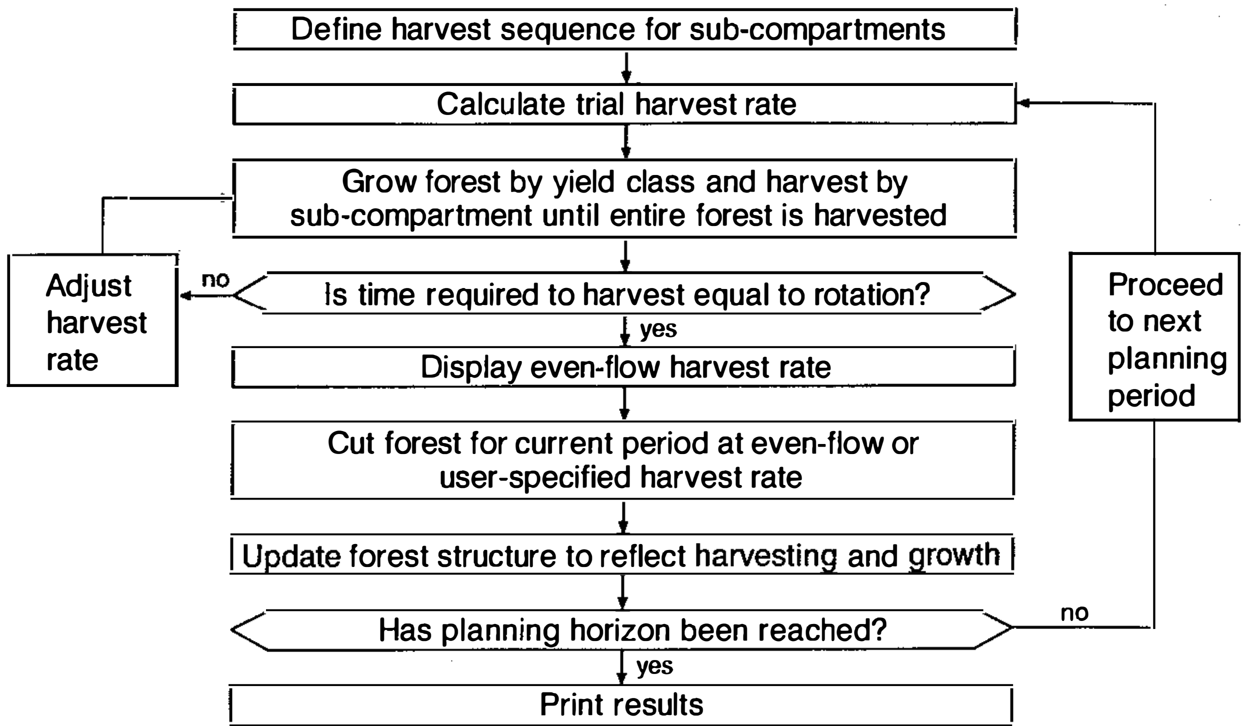

Figure 1. Flow chart of the compartmental planning model.

2. The model projects volume individually for each age class-yield class combination within each subcompartment based on user-supplied yield tables.

3. The sequential planning process of timber management is simulated. This provides a realistic picture of future volume flows including falldowns and allows for the assessment of undercuts, overcuts, and changes in management intensity.

The flow chart in Figure 1 is a simplification of the process used by CHARM. Once the harvest sequence has been assigned to the subcompartments, the procedure can be categorized into the three following steps.

1. Determination of the harvest rate required to cut the entire forest within a specified time period, generally the rotation.

2. Harvesting the forest at the even-flow harvest rate or at a user-specified rate for the current period. The forest structure is then updated to reflect harvesting and growth during the period.

3. Recalculation of even-flow harvest rate based on the updated forest structure. This step simulates periodic replanning.

These three steps are repeated for every period in the planning horizon.

Because subcompartments are defined geographically, it is possible to assign operating conditions and costs to them. These include haul costs, volume accessible by commuting, and sawlog volume. As a result, CHARM can track changes in subcompartment attributes over time. The model also has the capability to forecast age class distributions by period.

RESULTS AND DISCUSSION

A series of CHARM formulations was developed to compare operational sequencing (with and without replanning) with more conventional methods of sequencing such as Timber RAM and the area-volume check procedure based on "oldestfirst." The description of the runs is shown in Table 1. The operationally based sequencing was developed by considering variables other than total volume production. These include average haul cost, proportion of volume in sawlogs, proportion of volume accessible by commuting, and considerations for nontimber values such as for caribou habitat. The same age class distributions and yield tables were used throughout.

The period over which the even-flow harvest rates were determined for the CHARM runs was based on the area-weighted rotation of the seven yield classes. This rotation was approximately 110 years. To produce comparable Timber RAM schedules, the conversion period was set at 110 years.

Two interrelated functions in harvest scheduling are provided by CHARM. First, the model can be used as an aid in determining suitable operational harvest sequences. Secondly, CHARM calculates the harvest levels associated with a given sequence.

The initial step in harvest scheduling within this framework is to determine the order in which subcompartments are to be harvested. For any sequence defined by the user, CHARM produces a corresponding schedule of operating conditions and costs. By simulating alternative sequences, it is possible to determine one that best meets manufacturing and financial constraints. Among the variables considered within CHARM are haul cost, the proportion of total volume available as sawlogs, and the volume accessible by commuting. User-defined sequencing of subcompartments also allows for the explicit consideration of nontimber values. The volume flows associated with a particular sequence is the final element that must be considered in establishing the final harvesting schedule. It should be noted that the operationally based sequencing discussed here is concerned largely with conditions and costs occurring within the first half of the rotation. The average conditions over the second half of the rotation are examined, but balancing by decade is not done.

Comparisons of sawlog volume, haul costs, and commuter wood volume for two alternative sequences are shown in Figures 2-4. One of the sequences shown was formulated by considering operational factors; replanning was simulated every 10 years (Method 1 from Table 1). The other sequence was based on harvesting oldest subcompartments first; replanning was not simulated (Method 3 from Table 1).

The patterns shown in Figures 2-4 indicate that the operationally based sequence has more favorable and less variable conditions and costs in the first 50-60 years. The graphs demonstrate that forestry operations and costs can be strongly affected by sequencing and need to be considered in harvest scheduling. For example, Figure 2 indicates that following an oldest-first sequence would result in a 7% increase in haul costs over the first 20 years relative to the operational sequence. Variation in wood size, quality, and cost is a key consideration in primary forest products manufacturing. Note in Figure 3 the substantial damping in sawlog volume that has been scheduled in the operational sequence.

The volume flows from the runs described in Table 1 illustrate three distinct effects:

1. the effect of simulating replanning;
2. the effect of scheduling subcompartments rather than age class-yield class combinations; and
3. the effect of operationally based sequencing.

Figure 5 illustrates that the failure to model replanning can produce misleading volume schedules. The difference in the schedules is significant even in the short term. Furthermore, the only way to realistically assess the effect of overcutting or undercutting for one or more periods is to model

Table 1. Description of runs

Method	Description
1. CHARM	Operationally based sequencing with replanning every 10 years
2. CHARM	Operationally based sequencing without replanning
3. Area-volume check	"Oldest-first" sequencing, no replanning
4. Timber RAM	Harvest sequencing optimized with even-flow constraints in the conversion period. The post-conversion period average was constrained to be not less than the long-range sustained yield average (LRSYA)

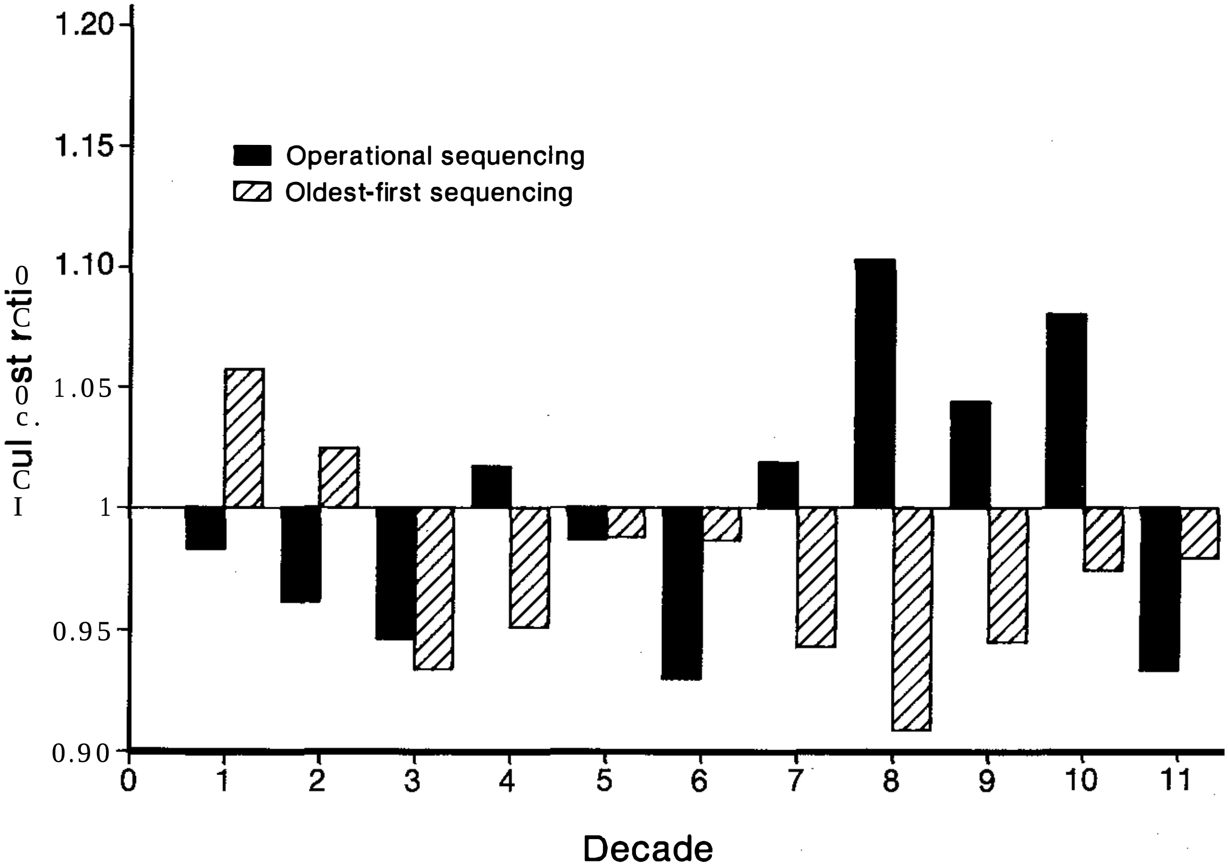

Figure 2. Haul cost ratio.

replanning. With CHARM, the user can specify harvest levels for any period, and then the model recalculates the even-flow harvest rate resulting from the specific cut. On the other hand, a model like Timber RAM allows the user to specify periodic cut levels, but it assumes that the recalculation of the harvest level will not occur until the end of the planning horizon.

The Period 1 harvest levels in Figure 6 indicate the effect of scheduling subcompartments rather than age class-yield class combinations. The Period 1 cut based on Timber RAM is 9.7% higher than the harvest level based on the operationally based scheduling of subcompartments. It is obvious that differences in model formulations can have substantial effects on harvest rates. More importantly, the difference in calculated harvest rates indicates the need to have a model formulation consistent with how the forest is to be harvested. For example, if the forest were harvested at the Timber RAM harvest rate for one period using an "operationally based" sequence, then the harvest rate for Period 2 would fall by 10.2%[1].

Operationally based sequencing affects volume flows as well as operating conditions and costs. For example, the Period 1 harvest rates in Figure 7 illustrate that the more-favorable operating conditions and costs associated with operationally based schedules (refer to Figs. 2-4) can negatively affect harvest volumes. The most suitable sequence will be one that best balances the positive and negative elements.

The CHARM model is intended to be used as a tool for harvest scheduling and determination of the

[1] This example assumes that the Period 2 harvest rate is calculated with a method consistent with forest operations; a period length of 10 years was used.

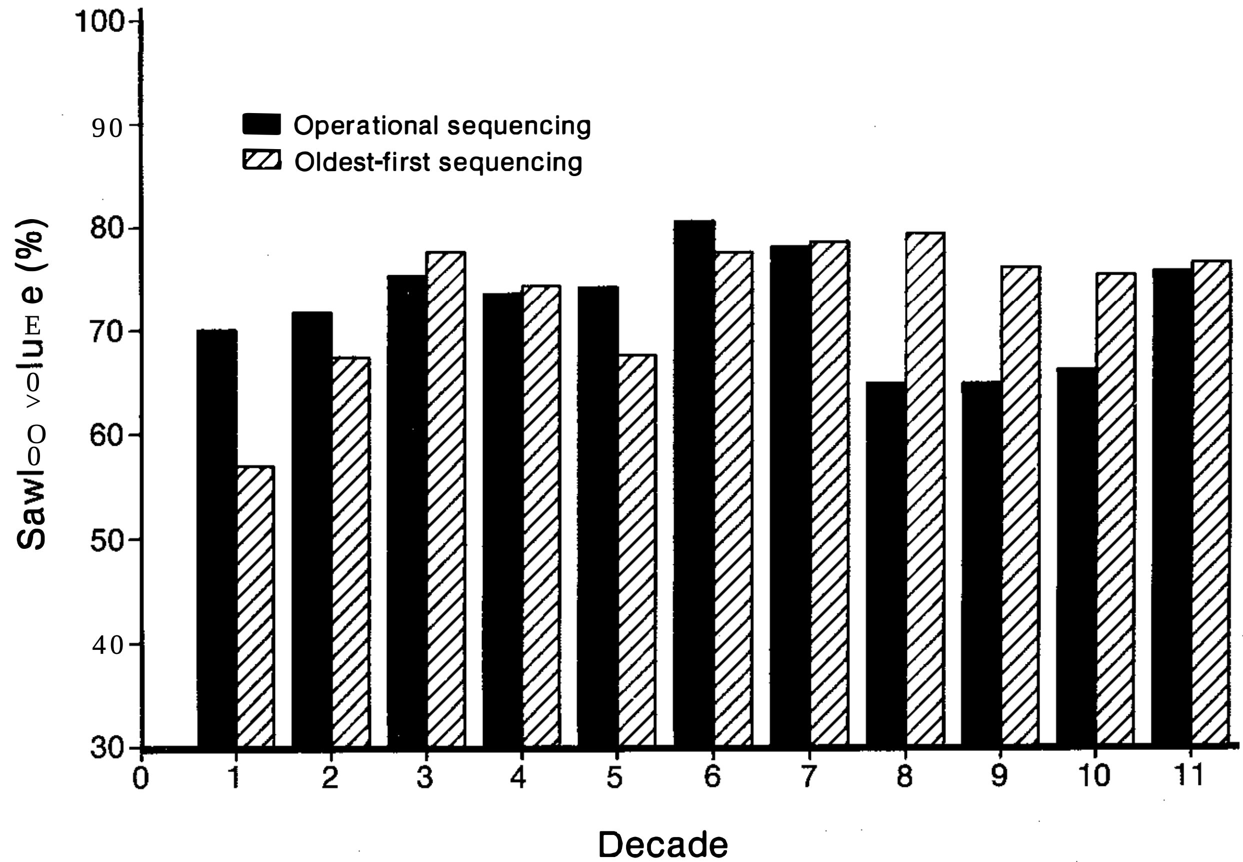

Figure 3. Sawlog volume.

associated conditions, costs, and harvest levels. It is a simulation model, and alternative sequences should be tested to determine sensitivities and appropriate harvest schedules. The model facilitates this process through a relatively simple structure allowing the user to easily create numerous model configurations.

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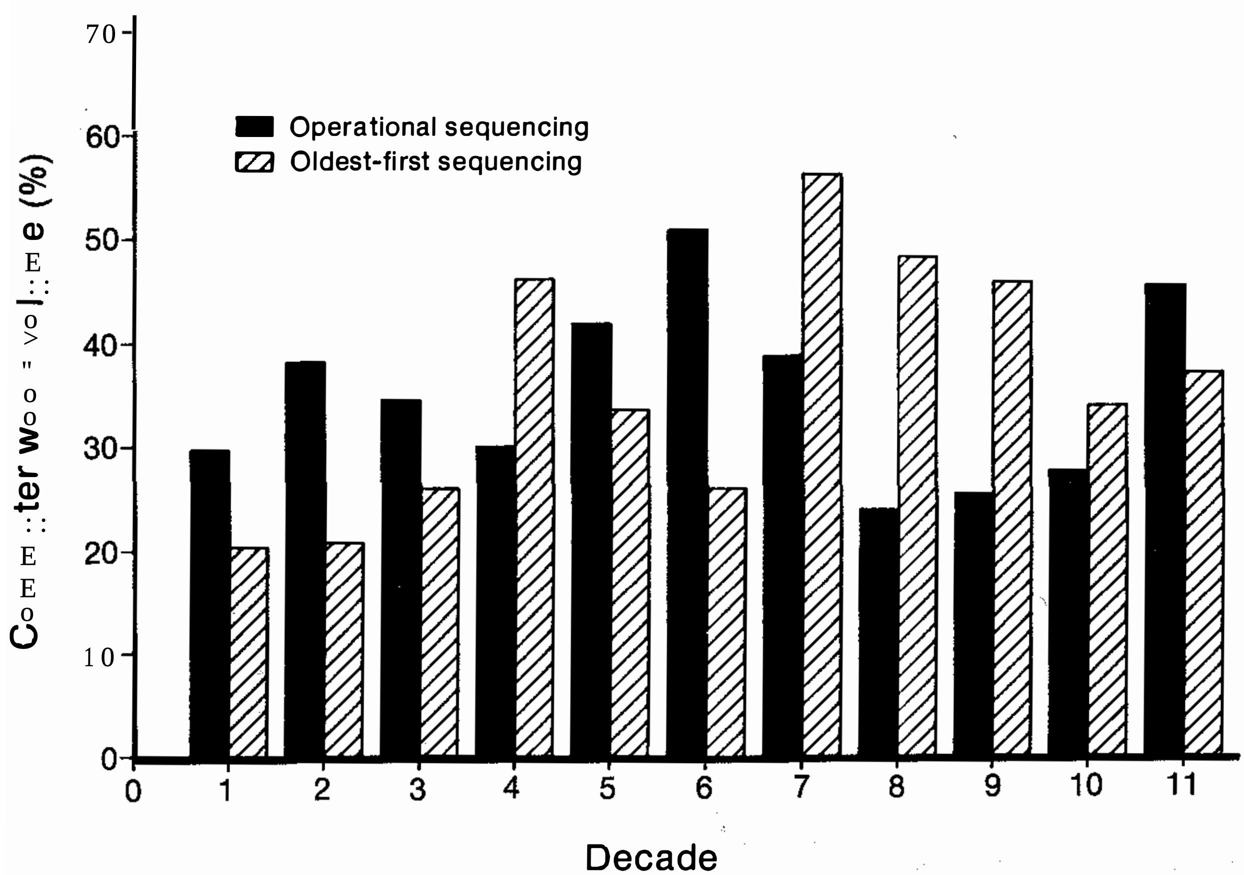

Figure 4. Volume accessible by commuting.

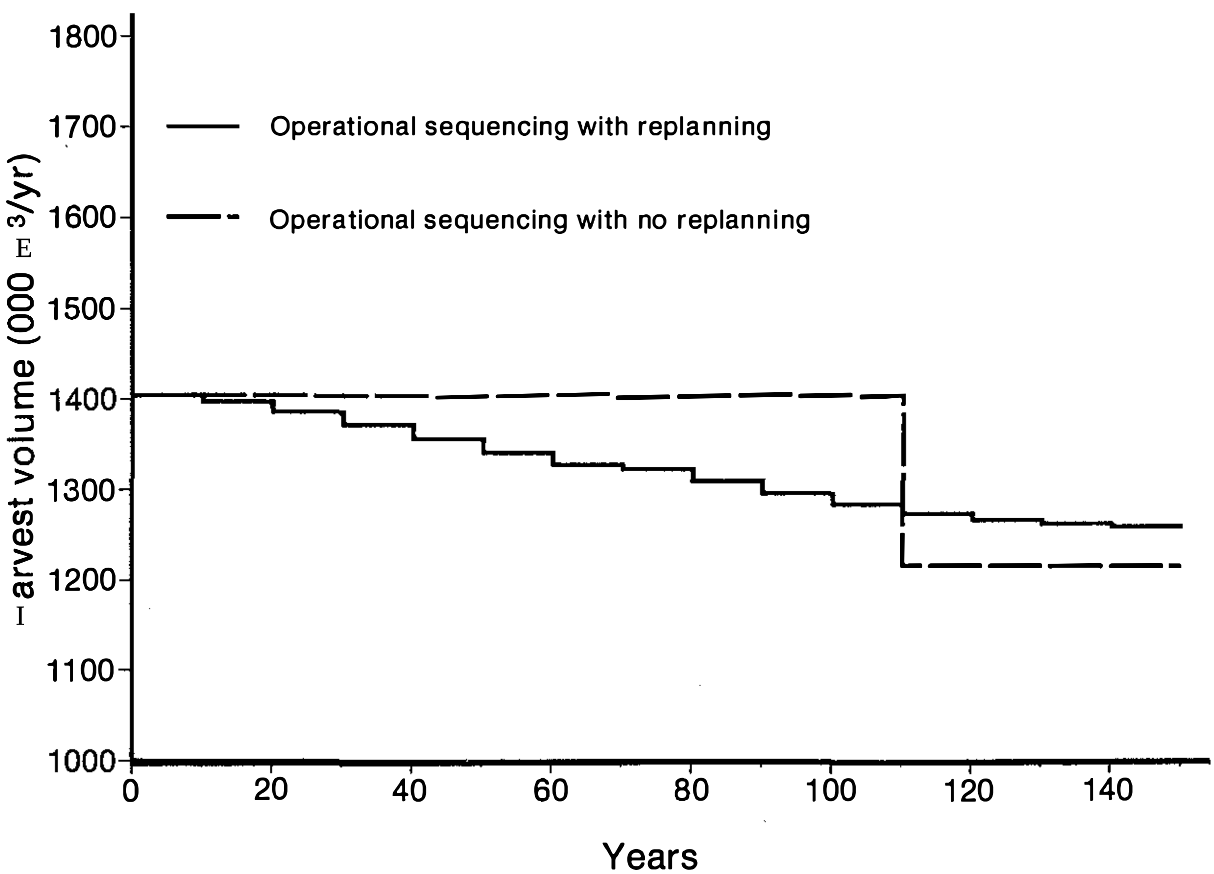

Figure 5. Volume comparison with operational sequencing and no replanning.

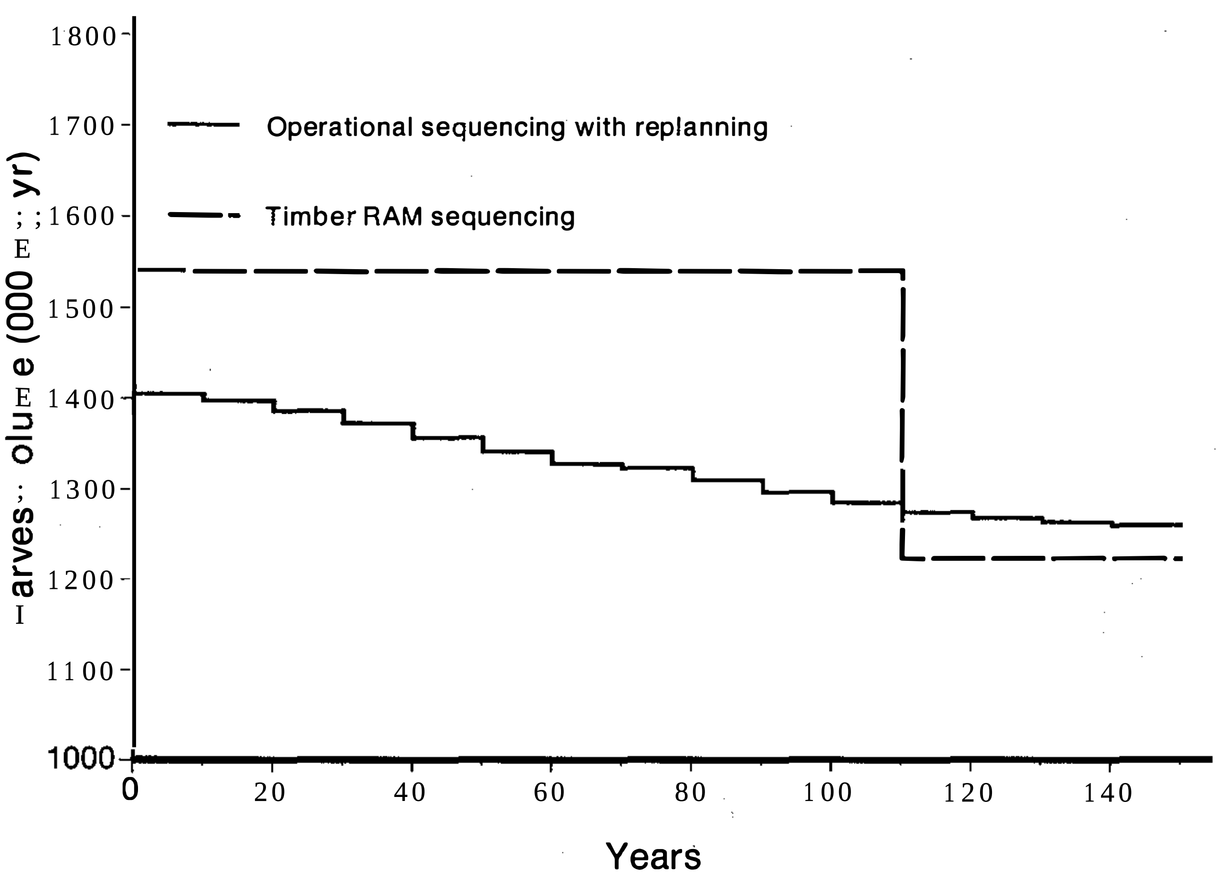

Figure 6. Volume comparison with Timber RAM.

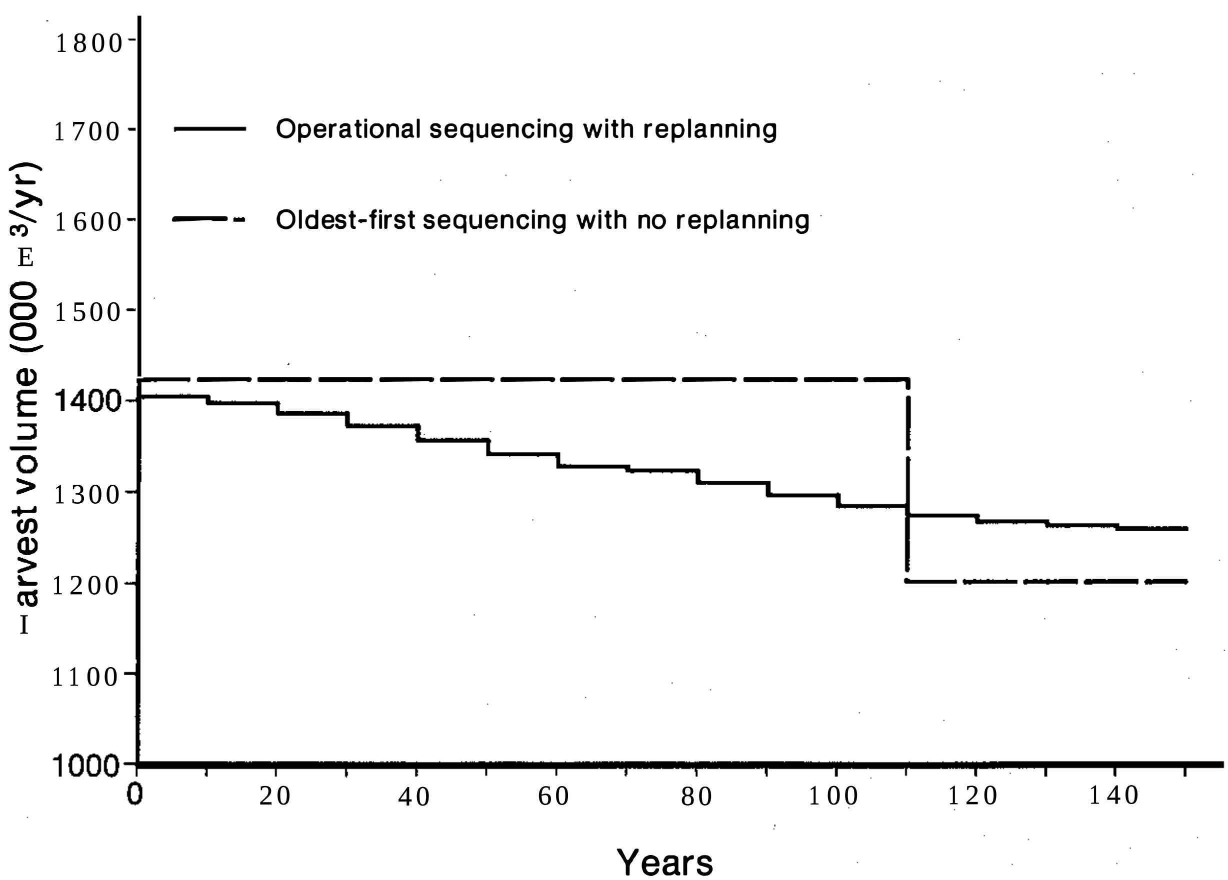

Figure 7. Volume comparison with oldest-first sequencing and no replanning.

QUESTION AND ANSWER SESSION

Question for Neil Stevens:

To what extent, how frequently, and what people in the organization are making use of the model you described here?

Neil Stevens:

Specifically, the model that I described here is just used by Procter and Gamble in their timber supply analysis for their management plan requirements. I think they also use it as the beginning or start of more-detailed plans, such as the annual operating plans. I believe the more-specific operating costs, such as the haul and capital costs for bridges and roads, are also used for budgetary purposes.

Question for Don Reimer by Ed Packee:

Looking at the boreal forest, I think that Alaska is in the same boat as many. I think Saskatchewan has a great deal of information compared to what I'm starting out with. If you were to start looking at a GIS system and you were looking at tree growth and a component of tree growth, what would be your parameters to put the organization of the plots together and your data base? What would you do first? How big would your plots be in this boreal forest, and how would you prioritize your data gathering?

Don Reimer:

Well, I don't think I'll answer all of your questions, obviously. I can give you some examples. The size of the plots is a trade-off between how much money you want to spend on plot measurement on a site-specific, small, tight location versus spreading your information across a larger geographic area. Given the size of the trees that you have in the boreal forest, I would think one-tenth of a hectare is going to be plenty big enough, and it may be that you want to start in the center. Put in a one-tenth of a hectare plot, start in the center, and measure some very detailed information, but put in the whole size. On the other hand, if you've got some mixed species situations or some large holes, patchy stands, then for those particular areas it may have to be larger. I think the thing you have to consider in not just inventory and growth and yield information is that—maybe growth and yield is a little more specific—you are trying to measure a variety of situations. If you stem map the plots, then you don't need nearly as many plots to cover a wide variety of stocking situations, and you can get away with a one-tenth hectare plot fairly efficiently. As far as priorities, that is up to you guys, what your information is. What is it that you need to know first? Obviously, you have to have site curves, you have to have tree volume equations, all that kind of stuff.

Question for Bob Lamont by Imre Bella:

Don was recommending experimenting with these extra information needs. Is it feasible to plan for these now?

Bob Lamont:

It takes about 20 years to go through an inventory cycle in Manitoba. So, if we were to change to start measuring some particular item, that's the kind of time frame we would be looking at to bring it in through the whole forest. That's a long time. I'm not sure that our needs are there at the present time from the Manitoba viewpoint. I think we can do with much less at the start, something that's probably already in existence, and I think I heard myself say words like that a year ago. So I don't have a concern with respect to getting started in it. In the case of Manitoba, our forest economist has obtained quite a range of programs and indicates that they are available for our use. But he still hasn't given them to us, and he's had them for more than 4 years. So perhaps it's an example of he who gets the programs isn't necessarily the one to use them. It's a little burning issue we have at home right now, in that he has it in his basement and not at work. So that's the kind of thing you're dealing with. I don't really worry too much about the future attainment of these things because that's going to be somebody else's problem, not mine. But if you bring it in, it's a matter of getting started and knowing what you are measuring. I hear the word mapping of the stand. We have been doing that with our new permanent plots, so perhaps we've done something right there. I won't say that there is a guidebook somewhere that tells you what kind of density pattern to look at, what you should be evaluating with that analysis. Am I getting close to your question or, am I missing it immensely? Benson knows the answer, so I'll give it to him.

Jamie Benson:

I agree with Bob. If you want to add something to your classification system, you are looking at a very long-term proposition, particularly in these days when the big money simply is not available for forest inventories. Twenty years probably is optimistic for a reinventory cycle. It's certainly possible, but I'm not sure we are finished downsizing. However, if you have some new information that you can collect and attach to your existing classification system and can collect this information through some sort of sampling design, then you can shorten that time frame quite considerably. Again, the key part is, is it something new that has to be attached to the land base, or can you attach it to the classification system? If it has to be added to the land base information in your classification system, a new piece of information such as we started adding about 9 or 10 years ago, you're looking at a cycle before you have any useful information out of it. If you can add it through a sampling system and attach it to your existing classification system, you're in business. I'm not entirely sure how you link distance-dependent information into an existing classification system. I think that's a toughy. I wouldn't mind chatting with Don to see how he does it, but I don't see any easy way of doing it, unless you can do it through the general crown closure classification. That might work, but they are pretty broad. You know, there are four density classes in Saskatchewan. I don't know how many other people carry, but it isn't very many. There's an awful lot of variation. I don't see any other way to link it, and you've got a terrific variation in those density classes in terms of stems per hectare.

Don Reimer:

I think it's worth discussing, because you are going to do forest management over a variety of densities and a variety of species mixes. You are already doing that, and you are going to have to get a lot more sophisticated in how you can handle those management alternatives relative to downstream and associated resources like pest management and wildlife habitat. One of the things the U.S. Forest Service has found is that they can take this type of model and run it in one stage less resolution, predicting stand tables so that you can use stand table-like information out of your inventory. They are actually using it (I don't know how successful they are) to tie into forest cover habitat, big game habitat projection, and pest management models, because that type of model can tie into these other kinds of models. Certainly, the big problem (from what little I know about inventories in Saskatchewan and Manitoba) is that your density and distribution problem is one of the limits of the resolution of using that kind of model. But you can run these kinds of models on lesser information. You just have to recognize that you don't have some of that additional information. I think that it's something you have to think about. There are probably 16 ways to skin a cat. To me, those are the minimum things that you are going to get away with in the future. You've got to have something on crowns and on distribution within the stand that's better than just average stocking.

Question for Don Reimer by Imre Bella:

I'd like to follow up on what Don said when you brought in the discussion relating to the U.S. Forest Service. My impression was that they're actually using stand-level information to do growth projections and yield estimates, and that's quite different than what we are trying to do here using, say, very crude cover type information. I'm just wondering whether it's even realistic at this point to try to enhance the data base that much before we improve the other end, the classification end of it. When we get on to stand information and growth and yield forecasts at the stand level, yes, definitely. I hope you are getting my drift.

Don Reimer:

I get your drift, and I agree it will probably take you 20 years to get there. But you may be surprised, it may not. The reason people are doing in-place inventory work is because they have to be site-specific in their planning. If you want to shut down a pulp mill, you can spend an awful lot of money upgrading an inventory before somebody is quite willing to shut down a $500 million a year pulp mill. That's what will drive the decision in the end. You see, one of the things GIS systems do is they make you do, by default, site-specific planning. One of the big problems you've got is that you produce all kinds of classy charts and graphs, but most likely your forest inventory data—and specifically where you're dealing with edge effects and things like that. Those are things we avoid in sampling. People don't want to sample edge effects. You want to get away from the edge, so you are into the stand. You've got no data for that. Zip. You cannot justify what you are doing. You can produce all the gorgeous charts in the world, and you've got zero information. You turn on the sample location map underneath that, and there's nothing there. So you will be forced to do something about that whether you want to or not by somebody else. All I'm saying is, every time you go out in the woods, measure a couple of other things.

ARTIFICIAL INTELLIGENCE FOR FOREST PEST MANAGEMENT

W.J.A. Volney
Forestry Canada
Edmonton, Alberta

ABSTRACT

A broad overview of research on artificial intellegence is developed to identify domains in which developments show greatest potential for application in forest pest management. Expert systems, which are of the greatest immediate potential, are described. Applications of expert systems to solving forest pest management problems are reviewed.

INTRODUCTION

What has become known as the science of artificial intelligence began with a 1956 conjecture that it should be possible to describe every aspect of learning so precisely that a machine could be made to mimic it (Patent 1986). This conjecture has become the "Holy Grail" of artificial intelligence, because it is difficult to define what is meant by intelligence and, despite 33 years of research in this area, no one has produced a machine that can even approach the human mind in its capacity to solve a variety of complex problems. Unlike the situation with the Holy Grail, however, it is possible, theoretically, to know when one has devised a machine that can think by applying the Turing test (Patent 1986). This test consists of trying to distinguish between the answers to questions posed of a person and a "thinking" machine. When it is impossible to distinguish between the two responses, one can conclude that a thinking machine has indeed been produced. Naturally, it might require considerable cleverness on the part of the questioner to trick the machine into revealing its identity. Nevertheless, machines have been built that approach the ability of humans in performing certain "thinking" tasks. A more modest definition of artificial intelligence is "how to make computers do things at which, for the moment, people are better" (Patent 1986). This definition is more convenient and skirts some of the philosophical problems of defining intelligence. By this definition, then, what constitutes artificial intelligence will change as we progress toward the "Holy Grail" of this area of human endeavor.

A major area of artificial intelligence research addresses problems in simulating human perception of language and vision. An inability to integrate the information derived from these sensory modes to produce a reasoned response has interfered with our attaining the ultimate goal of artificial intelligence research. Combined with our inability to effectively program for common sense these inadequacies make it even more difficult to achieve that goal. Part of the problem with language recognition arises from difficulties we have in discerning the rules of natural language, the ambiguity of language as we use it, and the contextual significance of the message. We absorb considerable quantities of information as we mature and can selectively recall the necessary information and process it to produce an appropriate response in most situations. Just how this is to be programmed is, at present, unknown. Similarly, although we are presented with large quantities of information in most scenes, considerable filtering occurs, and we are able to extract the pertinent information from a scene to produce a response. Such processing involves problems that are beyond our abilities to simulate in a machine, not the least of which is the supposition that the machine can be made to "know" what is important.

Despite these problems, some surprises have developed from the study of artificial intelligence. It is possible to simulate the processes by which experienced individuals, often with incomplete information, make decisions about complex systems. These simulations are now known as expert systems and have considerable application in crop management. My objective is to provide a brief description of these systems because of their potential significance to the practice of forest pest management.

EXPERT SYSTEMS

There are several definitions of what constitutes an expert system. A computer program that provides a solution to a problem by simulating the human reasoning process and using a body of knowledge can be called an expert system (Stone et al. 1986) In practice, the problem for which a solution is sought is normally sufficiently complex that it is worthwhile developing an expert system for its solution. Further, there should be a repeated need for these solutions. This typically arises because of changing conditions in either time or space (or both), exactly the situation faced by Canadian forest pest managers confronted with a dynamic system over a large geographic area.

The human reasoning process that is simulated in expert systems often involves the extensive use of heuristics as opposed to the algorithms commonly employed in other computer programs. Whereas an algorithm is a formal procedure guaranteed to produce a correct or optimal solution, the heuristic approach employs simplifications and rules of thumb to provide an acceptable solution (Latin et al. 1987). The expediency of using the heuristic approach is often dictated by the quantity and quality of information available or obtainable for solving the problem in a reasonable time at reasonable cost.

The contrast between algorithmic and heuristic solutions to a problem is best illustrated by comparing the use of Koch's postulates (an algorithm) for the identification of a disease-causing organism to the heuristic approach used in the field diagnosis of the cause of the disease (Latin et al. 1986). For example, the application of Koch's postulates to identifying the organism causing Armillaria root rot would require that

a. the pathogen is associated with all trees showing the symptoms,
b. the pathogen is grown in pure culture,
c. healthy trees can is inoculated with this culture,
d. the inoculated trees develop the symptoms observed in nature, and
e. the pathogen can be re-isolated from the inoculated trees.

This process would require a minimum of several months but would provide the best information concerning the identity of the pathogen. By contrast, field diagnosis of the presence of Armillaria root rot in a stand would depend on finding a combination of symptoms that includes all of the following:

1. dead trees are associated with trees having thin crowns and/or chlorotic foliage,
2. the affected trees occur in vaguely defined pockets or centers, and
3. the characteristic white mycelial fan occurs under the bark of the root collar or roots of recently dead trees.

This process would require at most a few hours (if travel time is required) but would provide information that may be subject to some probability of error.

A further distinction between ordinary computer programs or computer simulations and expert systems is that the former process data whereas knowledge is grist for the latter. Data are observations or facts that are summarized to provide information. Information from one source can be interpreted with respect to that derived from other sources to form knowledge. In the example above, the data obtained from observing conditions 1 through 3 can be summarized for the forest stand and interpreted along with other research results (including those derived from using Koch's postulates) to provide knowledge about the epidemiology of Armillaria root rot in stands. This knowledge can thus be applied to make predictions about the impact of the disease in particular stands.

Expert systems are composed of two essential components and a variety of utilities that enhance their capabilities and versatility. The component that is unique to the application for which the expert system was designed is the knowledge base. This knowledge base is the totality of information derived from human experts who have an understanding of the structure and functioning of the natural system. This knowledge is organized so that it can be addressed and employed efficiently by the expert system. Although there may be several ways to represent the knowledge base, the most common method is to formulate a rule base composed of a series of logical statements, usually in the form of IF...THEN statements. The rule base may include facts, principles, generalities, opinions, and hypothesized relationships. Expert systems can be programed to update the knowledge base in response to information derived from the natural system. This may include changes to the structure of the rules (IF...THEN statements) in addition to adjustments to the parameters of any algorithms that are incorporated into the expert system. Weighing the truth value of opinions and hypothesized relationships and updating these weights may also be used in contributing to updates in the knowledge base. Making changes in the knowledge base in response to experience is analogous to learning; hence the inclusion of expert systems in the field of artificial intelligence research is justified.

Operation of the expert system (which involves checking current information about the natural system against the rules in the knowledge base) is performed by the other essential component of expert systems known as the "inference engine." The inference engine searches the rule base, performs up-dates as required, and provides a solution to the problem at hand. It has been found expedient to isolate the problem-solving logic from the knowledge base because it is not necessary to alter the structure of the inference engine in response to the changing conditions of the natural system, which are reflected as updates to the rule base.

The expert system's solution to the problem may be a decision or a prescription. One of the utilities of the expert system is the reporting facility, which can provide a report on how the solution was derived. The forest manager would be irresponsible if he accepted (but did not check on) a suspect decision, knowing that the expert system contained rules that were based on opinions and hypothesized relationships.

Other utilities may be incorporated in the expert system to automatically provide managers with options for solving their problem. Although not characteristic of expert systems per se, these utilities would include a connection management system to manage the flow of information among the various computers connected to the system, a data-base management system to manage data from other sources, and a user interface to permit the manager to interact with the expert system. A utility that will probably be incorporated in most forest pest management expert systems in Canada will be a geographical information system to provide spatial information required to manage pests whose ranges cover large geographic areas (Coulson et al. 1989).

SYSTEM DEVELOPMENT CONSIDERATIONS

There are four requirements to be considered in the development of expert systems. The first is the availability of human experts conversant with the natural system being examined. These experts should possess the knowledge to adequately describe the functioning of the system. This knowledge need not be perfect and, where understanding of the natural system is deficient, best guesses will suffice to develop a prototype expert system. Sensitivity analyses, future research, and indeed updates by the system itself can be used to fill gaps in the knowledge base. Having identified the experts, the next step is to obtain, organize, and structure the knowledge in a form that can be programmed for the knowledge base. This job is the responsibility of "knowledge engineers." The other two considerations in system development are the choices of software and hardware with which the expert system is to be developed and implemented. Although it is not essential, the programming language used in development of the rule base is often one of the several developed specifically for artificial intelligence applications. Hardware considerations depend on the application, but with the recent increase in power of personal computers this is less of a constraint. Personal computers offer an opportunity for placing expert systems at the disposal of individuals working in locations, such as district offices of large forestry agencies, which are remote from centers of computing.

There are significant developmental constraints. A major concern is the availability of experts to solve the problem at hand. In applications involving biosystematics, for example, experts on particular taxonomic groups may not be trained or available. The second constraint is that the experts, once identified, may not be willing to participate in the project. Other demands for their expertise may preclude their participation. The cost of expert system development is the third major consideration influencing the decision to proceed. An expert system for diagnosing bacterial blood infections involving 200 pathogens took 10-person years to develop, but this involved considerable pioneering work, including the development of a programming language suitable for use in artificial intelligence programing (Patent 1986). Depending on the application, system development in forest pest management may require anywhere from two to eight person-years. Because of this cost the need to develop an expert system to solve a problem has to be carefully assessed. In large forestry concerns, the savings in wood costs, discounted to present net value, resulting from informed decisions on the timely harvest of stands threatened by pests can be used in evaluating the cost of expert system development. Other techniques are available to be used in evaluating the benefits, costs, and need for systems development.

FOREST PEST MANAGEMENT APPLICATIONS

Four major areas in which expert systems can be applied in forest pest management are diagnostics, integrated pest management, training, and technology transfer. The first is a relatively straightforward application of information to be found in insect and disease identification manuals and the experience of knowledgeable individuals who provide this service in their day-to-day activities. The need for this service can be evaluated by the history of requests for diagnostic services of the Forest Insect and Disease Survey (FIDS) of Forestry Canada and the Biosystematics Research Centre of Agriculture Canada in Ottawa. At present, the Northwest Region's FIDS unit handles approximately 2500 such requests annually, but the demand for this service is known to be substantially larger in this region's forestry community. An expert system for forest pest diagnostics could significantly improve the quality and volume of service currently provided to the forestry community of this region. The expert system would not obviate the need for specialists; rather, it would permit a more efficient use of their time to handle less routine identifications.

Integrated pest management applications of expert systems in forestry are at present under development for the hemlock looper in Newfoundland, and there are proposals to develop systems for other forest pests of the mixed-wood forests in the Northwest Region. Significant strides have been made in the development of integrated pest management systems for a variety of forest insects in North America through accelerated research and development programs. These insects include the spruce budworm, western spruce budworm, gypsy moth, mountain pine beetle, western pine beetle, and southern pine beetle. In each case decision-support systems can be easily developed or have been developed, and an expert system is under development for the southern pine beetle (Coulson et al. 1989). The impact of these developments on resource management has not been fully analyzed to date; however, the benefits from expert system development allow application of the methodology to pest management problem solving at different administration levels while ensuring that the needs and problem-solving style of the individual manager are addressed (Coulson et al. 1989). No individual can effectively utilize all pertinent information in solving complex pest management problems in short time intervals or explore several plausible solutions simultaneously. To embed these solutions in an integrated resource management decision process further complicates an already difficult problem. Expert systems present an opportunity to address these concerns. It is believed that the application of expert systems to forest pest management problems will provide the greatest opportunity for Canadian forestry practitioners to manage pests in integrated resource management systems.

Training of personnel, which is a third major application of expert systems, can be accomplished by encouraging individuals to explore expert systems developed to solve particular problems. The expert system accompanied by on-line user manuals, knowledge base documentation, and familiarization or training protocols could be a training tool in itself. Expert systems designed specifically to train people have, of course, been developed. In addition to the expertise of the pest management specialist, the services of a teaching specialist would be required. Because of the variety of products available from an expert system, students could tailor the learning session to their individual needs. The almost immediate response of the system provides a learning situation that would appeal to individuals who wish to explore the system with a clever selection of conditions. In essence, the exercise has the appeal of a game with all the attendant benefits of rapid learning and skill development.

Expert systems also address the need to disseminate research results in a cogent and coherent fashion in a manner accessible and useful to the nonexpert practitioner. Although it is useful to consult the specialist in making decisions, the specialist may not be available. Thus if properly designed, an expert system can be a teaching tool, a means of technology transfer, and an aid to decision making in forest pest management in a decentralized forestry community.

CONCLUSIONS

Managers make decisions about natural systems that are not completely understood (double entendre deliberate). The expert system permits these decisions to be made by mimicking the expert in the use of facts, information, knowledge, and some of the expert's opinions. Unlike the expert, the expert system can assess a large number of possible solutions and select among the best of them in a short period and report the route by which the solution was obtained. The extremely rapid decline in the cost of computing hardware and the relative scarcity of experts will probably combine to spur development of these expert systems for forest pest management applications in integrated resource management systems. These systems will not replace the experts but can be their tools to focus their attention on resource management problems in vital need of research.

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WOOD QUALITY IN MODELING STAND INVESTMENT AND HARVESTING DECISIONS

R.E. Pulkki
Lakehead University
Thunder Bay, Ontario

ABSTRACT

Our forest industry is changing from a commodities-driven producer to a producer of higher quality, value-added products. As a result, greater emphasis must be placed on wood quality in stand investment and harvesting decisions. The basic wood qualities and the interrelationships with harvesting and processing are outlined. The implications of the above on modeling are then reviewed.

INTRODUCTION

In stand investment and harvesting decision-aiding models, future forest product market trends and wood quality factors are often ignored. This often leads to solutions that favor maximum growth, and sites are therefore regenerated with species that cannot be used for high-quality and high value-added groundwood-based papers. Row thinnings are usually the method of thinning used due to expediency, and the overall improvement of the stand for log production is secondary. Similarly, harvesting systems yielding the lowest mill-gate cost are generally favored. The overall production cost and quality for the final product must be the decision criterion, however.

The objective of this paper is to highlight some of the major market trends, the importance of wood and tree qualities, and how these can affect harvesting and processing costs and the quality of the final product. Finally, the implications of the above on modeling stand investment and harvesting decisions are outlined.

MARKET TRENDS

In northern regions, wood forms the largest cost component in the manufacture of forest products. This is especially true for low value-added, commodity products. For example, in eastern Canada wood costs account for 60% of the production costs in a softwood kraft pulp mill (Table 1).

Due to high growth rates and thus low fiber costs, there is increasing competition from developing countries in the area of commodity forest products (e.g., market pulp). Fortunately, the fiber qual-

Table 1. Wood cost as a percentage of production cost (Ehrnrooth and Kirjasniemi 1987)

Region	Softwood lumber	Softwood kraft	Hardwood kraft	Kraft linerboard	Newsprint	Uncoated fine paper
Western Canada	52	56	-	52	-	-
Eastern Canada	52	60	48	54	33	-
Southern USA	-	58	43	47	30	26
Finland	68	79	67	70	47	41
Sweden	65	76	62	66	50	35
Portugal	-	-	43	41	-	-
Brazil	-	-	53	47	-	-
F.R. Germany	-	-	-	-	21	-
Austria	67	-	-	-	-	-

ity in our northern species (e.g., northern spruce) is generally better and more suited for higher-quality products. We generally also have an advantage over developing countries in the areas of technology, know-how, skilled labor, capital, and energy supply and cost.

The best way to compete with southern producers of bulk forest products is to produce high-quality and specialized high value-added products. This conclusion has been reflected in all market forecasts and trends, which point toward the increased production of high-quality printing and writing papers and a greater variety of product lines. Two of the most rapidly growing products are groundwood-based supercalendered (SC) and lightweight coated (LWC) papers (Woodbridge, Reed and Associates 1987). For these products, high-quality fiber (preferably spruce) is required.

In the solid wood products area there are similar problems. Production will have to move away from commodity lumber products to higher value-added and specialized products of high quality. As we begin to harvest second-growth forests, wood quality will also change. Any forest investment model must take into account the positive and negative effects of treatments on the wood quality produced.

To be competitive in future markets we must ensure that the fiber resource is of high quality. When harvesting that fiber we must ensure that there are minimal fiber and quality losses from the forest to the mill. In the end this may result in higher logging costs, but there will be an overall reduction in the cost of the final product and an increase in its quality. Similarly, if we intend to continue increasing the level of forest management, the cost for standing timber must also increase. A good comparison is the Nordic countries, where the stumpage rates for comparable species assortments and site types are six to ten times greater than those in Canada. The high stumpage rate is reflected in their very high delivered-wood cost (Table 2). This further emphasizes the need for us in the future to utilize our wood to its full potential and to get the highest possible return from it through higher value-added products.

WOOD QUALITY

General

There are a number of characteristic features of wood that influence the different mill processes. These characteristics vary between species, between trees of the same species, and within a tree itself. Genetic and environmental (e.g., forest management activities) components, as well as harvesting, are the factors affecting wood traits. It is important to note that the most suitable characteristics for one mill process are not necessarily the best for another. The following is a list of the characteristic features of wood:

- relative density;
- extent of decay or insect damage;
- fiber morphology;
- moisture content;
- wood assortment type and size;
- chip size distribution;
- branch and knot wood;

Table 2. Average delivered pulpwood (roundwood) costs for various regions (Wood Resources International Ltd. 1988)

Region	Softwood (U.S. $/m^3)	Hardwood (U.S. $/m^3)
U.S. south	24	20
U.S. northwest	23	22
Canada east	39	25
Canada west	31	28
Northern Europe	58	52
Central Europe	54	42
Portugal, Spain	31	46
Brazil	17	15
Chile	9	19

- inner and outer bark;
- sapwood and heartwood;
- mature and juvenile wood;
- chemical composition of the wood;
- springwood and summerwood; and
- amount of sand and other contaminants.

Influence on Harvesting

The various harvesting alternatives available and stand and wood quality factors from the forest to the woodroom are presented in Figure 1. As can be seen, it is a complex network, even with mill processing and final products omitted. It is beyond the scope of this paper to go into all the details of the interrelationships between wood quality, harvesting, processing, and final products.

It is safe to say, however, that any real improvements in the stand and wood quality through stand investments have beneficial effects when it comes to harvesting costs. Therefore, any stand investments must be credited with expected reductions in harvesting cost. Some of these savings would be as follows:

- Higher growth rates produce more harvestable volume per hectare, thus reducing logging costs per hectare and also concentrating operations closer to the mills (i.e., commuter operations could be run, eliminating high-cost camp operations).

- Areas closer to towns and mills will have good access. Road costs would thus be a fraction of that in exploitive forest management.

- By operating closer to the mills with good access, uncertainty in wood flow is decreased, and inventories and inventory costs could be drastically reduced.

- By having small inventories (i.e., short period from felling to use in the mill), wood quality reductions due to storing can more or less be eliminated.

- Hauling costs would be reduced due to shorter transport distances and a better road network.

- Larger tree size increases productivity.

- Fewer branches and better form increase productivity.

- Drainage allows better forest access.

- Less undergrowth increases harvesting productivity.

Influence of Harvesting

Harvesting has both direct and indirect effects on wood quality. These are both outlined in Figure 1. Direct effects occur from actually changing the form of the wood, e.g., full tree chips, pulpwood, or logs. Other direct effects occur through actual damage to the wood, e.g., breakage, removal of bark, or covering it with mud. Indirect effects occur through wood storage. For example, in mechanical delimbing a large share of the bark is removed in the spring. This in turn allows the wood to dry very quickly. If the wood is destined for a mechanical pulping process this practice would cause serious negative effects on processing and quality of the final product.

IMPLICATIONS FOR MODELING

As should be apparent, whatever is done at harvest can seriously affect the processing of the wood and the quality of the final product. Any decision in choosing harvesting systems and machines, their use, and in their planning and control, must therefore also take into account the effects on the mill processing. As a result, all decision-making and models must be based on cost from forest to final product and product quality. Similarly, any model dealing with forest investments must take into account effects on wood quality and harvesting. The ideal model would therefore be an integrated model including forest management, harvesting, processing, final products, and possibly markets. Whether this model could be built today at a reasonable cost is another matter.

Expert systems for harvest planning that follow the above principles are coming closer to reality. These models are generally based on artificial intelligence programming systems (e.g., PROLOG and Object Oriented Programming Systems (OOPS)) and heuristic, rather than linear programming.

Heuristic programming is not an optimizing method but one that searches for satisfactory solutions. This is achieved through "intelligent" examination of possible solutions with the objective of obtaining a "good" solution. The method relies on experience, inductive reasoning, and intuitive and empirical rules to move from one feasible solution to another (Dykstra 1976; Taha 1982). Once a sufficient number of possible solutions has been obtained, the one giving the best result is chosen. The sufficient number of possible solutions depends on the

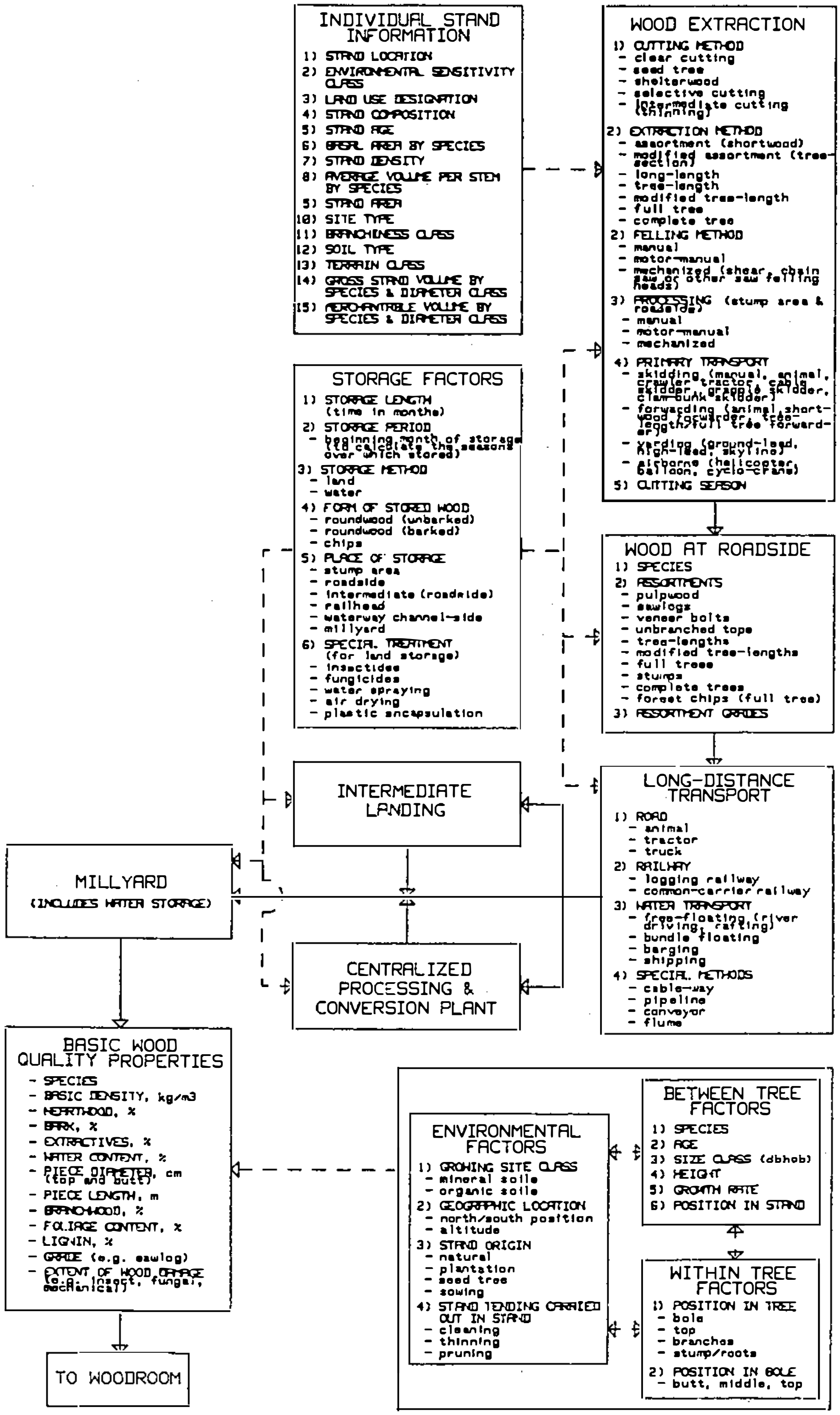

Figure 1. Wood procurement flow chart.

desired closeness to the optimum, complexity of the problem, and level of detail involved. Among operations research methods it is the one closest to traditional problem solving; the major difference is that the search for feasible alternatives for the solution is done with a computer. There is no clear-cut procedure for heuristic programming, and the methodology applicable depends on the problem in question (Pulkki 1984).

Due to the complexity of the problem and the large number of variables involved, any decision-aiding model should have the ability to outline its flow as it works through a problem. This is important to help the user understand the model and thus gain confidence in the results. Also, errors and wrong assumptions can be found more readily. Another important model feature would be the ability to show the effect on other system parts of changing one system variable and to explain why the changes occur.

CONCLUSIONS

Due to increasing competition from lower fiber-cost regions our forest industry will have to move in the direction of higher quality and value-added products. Our high wood quality gives us an inherent advantage in this regard. As a result, any decisions concerning stand investments or harvesting must also account for this shift from the production of commodity products to the production of high quality, specialized products.

Stand investments, harvesting, and wood quality are interrelated. Investments to improve the forest almost always result in lower harvesting costs. Improving or even just maintaining wood quality through stand investments or proper harvesting will result in lower processing costs at the mill and will allow the production of higher quality products. All of these benefits and interrelationships must be accounted for when modeling forest investment and harvesting decision-making.

Basic research in modeling the production process from the forest to the final product is in progress. These expert systems are generally based on heuristic programming and the use of high-level artificial intelligence based programming languages. Due to the complexity of the problem each model must be built to fit each individual situation because each forest area and mill is unique.

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THE FORCYTE EXPERIENCE: A DECADE OF MODEL DEVELOPMENT

J.P. Kimmins
University of British Columbia
Vancouver, B.C.

K.A. Scoullar
Life Science Programming
Naramata, B.C.

M.J. Apps
Forestry Canada
Edmonton, Alberta

W.A. Kurz
University of British Columbia
Vancouver, B.C.

ABSTRACT

The World Commission on Environment and Development has issued a challenge in its report, *Our common future*: to demonstrate that all future developments are consistent with a sustainable environment and sustainable renewable resources. In forestry, this requires projections over at least several rotations (a three-rotation minimum has been suggested by an IUFRO working group) concerning the sustainability of yield and site productivity under alternative management strategies. In the absence of empirical experience over such long time spans, interim estimates of sustainability can be obtained by calibrating and using models like FORCYTE-11. The development of the FORCYTE series of ecosystem management models was a component of the ENFOR program of Forestry Canada, which was initiated in response to the Arab oil embargo of the mid-1970s. Initially a simple input-output model to examine soil fertility aspects of the sustainability of intensive biomass-for-energy, FORCYTE has been developed to become an ecosystem management model with which to simulate the short- and long-term effects of a wide variety of rotation-length management strategies on stand-level production, yield, yield sustainability, and economic and energy benefit-cost ratios. Although this version of the model cannot address questions that relate to climate change (the greenhouse effect), it can examine the effects of management on long-term site (i.e., soil) productivity.

INTRODUCTION: ORIGINS OF FORCYTE

The apparently inevitable doubling of the world population from the present 5.2 billion to about 10-11 billion (Repetto 1987; World Resources Institute and International Institute for Environment and Development 1988), together with the increasingly serious deterioration of the global environment (e.g., Morrison 1984; Shands and Hoffman 1987), led the United Nations to establish the World Commission on Environment and Development. Their report, *Our common future* (World Commission on Environment and Development 1987), concluded that although the industrialized nations bear a grave burden of responsibility for current and past environmental deterioration, the greatest long-term threat to the environment comes from poverty in the populous developing countries. The commission concluded that the long-term survival of the human species on earth depends on the elimination of this poverty, and that this will require the sustainable development of the world's resources. This in turn implies the need for planning tools with which to establish the sustainability of all future resource developments.

The so-called developed western nations have become hopelessly addicted to the use and annually increasing use of fossil fuel energy. Our current standard of living, lifestyle, and entire economics are so fossil-fuel energy-dependent that the prospect of major reductions in the availability and use of fossil fuels is as threatening to current developed societies as the impending withdrawal of supplies of heroin must be for a heroin addict.

The Arab oil embargo of the mid-1970s sent a shock wave through the industrialized nations, who vowed to undertake the necessary steps to reduce their dependence on fossil fuels. The International Energy Agency was created, with subprograms to examine the feasibility and sustainability of biomass-for-energy production systems. A parallel activity in Canada, the ENFOR (ENergy from the FORest) program of Forestry Canada (funded by Energy, Mines and Resources Canada) also investigated the sustainability of bioenergy production systems in forestry. A small project in this program was to review the soil fertility implications of whole-tree harvesting bioenergy tree plantations on short rotations and to prepare a simple nutrient input-output model by which to establish the site nutrient budget for such harvesting systems. This was to become the basis for speculations about the sustainability of yield in energy plantations. Initial work on this input-output model revealed that such a simplistic model would end to give simplistic answers. The significant questions could only be answered in a significant and believable manner by a much more complex approach. It was therefore concluded that a mechanistic, ecosystem-level computer simulation model capable of simulating all the major bioenergy plantation management options was needed. This conclusion was the genesis of FORCYTE: the FORest nutrient Cycling and Yield Trend Evaluator. Credit for this genesis must go to the pioneering work of the late Dr. Peter Rennie (Rennie 1955, 1957) and Dr. A. (Jock) Carlisle, whose tireless insistence on the need for such an evaluation tool made the development of FORCYTE possible.

A BRIEF HISTORY OF MODEL DEVELOPMENT

FORCYTE developed out of a 1977-78 ENFOR contract. FORCYTE-1 was a simple historical bioassay (see Kimmins, this volume, or Kimmins 1985, 1986, 1988) mathematical model of forest growth including herbs, shrubs, and trees, with simulated nutrient cycling but no feedback between nutrient availability and forest growth. This initial model was a foundation from which a useful model could be developed, but it could not be used to address the critical questions. Over the next 5 years the model was developed to FORCYTE-10 (Kimmins and Scoullar 1983). The various intermediate versions of the model (FORCYTE-2 to FORCYTE-9) represented significant stages in the development of this benchmark version (addition of nutrient feedback, a simulation of site quality change, various management activities, tabular as well as graphical output, energy analysis, and economic analysis). FORCYTE-10 has been field tested in Oregon (Sachs and Sollins 1986), Finland (Kellomaki and Seppala 1987), Alaska (Yarie 1986), Canada (Feller et al. 1983), and the southern pine region of the United States (Fox et al. 1984).

Useful as a teaching and research tool and suitable for use as a qualitative decision support tool in some aspects of bioenergy plantation management or conventional forest management, FORCYTE-10 proved to have several shortcomings that limited its use as a more quantitative decision support tool. Consequently, another 5 years was invested in the development of its successor, FORCYTE-11. Whereas the series FORCYTE-1 to FORCYTE-10 constituted the definable stages in development of the benchmark FORCYTE-10, development of FORCYTE-11 involved a major restructuring of the model. This was necessary to overcome those unacceptable limitations of FORCYTE-10 that were the result of the modeling approach of the model. FORCYTE-11 is a modeling framework rather than an individual model, and it permits the user to simulate a much wider range of bioenergy, forestry, or agroforestry management systems than was possible with FORCYTE-10.

DESIGN CRITERIA AND MODELING APPROACH

The development of FORCYTE-11 has been guided by a list of design criteria. These are as follows:

1. The model should have a sufficiently generalized structure that it can be applied to a wide variety of even-aged stands managed under monoculture, mixed species, or alternating species forest crop (traditional or bioenergy), or agroforestry management systems. It should be a modeling framework that can be customized for a wide variety of uses rather than a single, fixed-structure model.

2. The model should have a modular structure that separates the calibration and testing of individual ecosystem component modules from the evaluation and use of the ecosystem management simulator. This structure also keeps the size of the management simulator within reasonable limits and reduces the problem of model size and complexity that normally limits the amount of detail that can usefully be added to an ecosystem-level model.

3. The model should provide the user with the opportunity to simulate the effects of all the major management treatments on nutrient cycling, soil nutrient availability, and competition for nutrients and light. The effects of these site resources on plant growth and the relative competitive abilities of different species should be simulated explicitly.

4. Ecological processes that determine growth should be simulated as mechanistically as possible, avoiding the use of mathematical surrogates for an ecologically and biologically sound description wherever possible.

5. The model should, wherever possible, be driven by empirical, inventory-type data, rather than by data on process rates that require prolonged and detailed scientific measurement. Although the requirement for field, growth chamber, and laboratory measurements of the rates of some processes is unavoidable, inventory-type data should be employed wherever it is possible. This design criterion depends on the combination of a field-measured outcome of some process (e.g., annual growth of plants; annual weight loss of a decomposing log) with an understanding of the process. This combination is used to infer the rate at which the process must have occurred. Thus, many process-rate estimates are obtained indirectly from field inventory-type data.

6. The model should produce sufficient diagnostic output to permit the user to identify errors in data entry, bad data, or unacceptable model performance. This diagnostic output should be produced by each of the model's subcomponents and should provide a usable basis for model (or individual module) rejection.

7. Wherever possible, the user should have the option to switch off or alter the simulation of individual processes where he or she does not accept the way these processes have been simulated. This provides the user with a means of modifying many of the model's assumptions. The user must have control over all process rates by way of input data files.

8. The number of calibration "twiddle knobs" should be kept to an absolute minimum, and where these are inevitable they should be controlled by the user in the input file. They should not be hidden in the code. As few assumptions as possible should be embedded in the computer code; wherever possible, assumptions should be controlled by the user via the input data files.

9. The modeling approach should be that of hybrid simulation: the presentation of the historical patterns of plant growth and ecosystem function, and an evaluation of the repeatability of these patterns when the rates of certain processes are changed by the simulation of altered management practices.

10. The use of the model by resource managers should be made as user-friendly as possible by the development of supervisory computer software that facilitates the user of the model in multiple comparison runs and the presentation and interpretation of the output of these runs.

Details of the modeling approach will not be presented here as they have been presented in Kimmins (1985, 1986, 1988) and Kimmins and Scoullar (1990).

STRUCTURE AND PROCESSES REPRESENTED

Details of the structure and processes of FORCYTE-11 can be found in the user's manual (Kimmins and Scoullar 1990). The structure of this version of the model is summarized in Figure 1, and the major compartments and processes that are simulated are shown in Figure 2.

The simulation options and processes that are represented in the benchmark version of FORCYTE-11 are listed in Table 1. Some of these representations may be modified or improved upon in future versions.

Planned Future Developments

The benchmark version of FORCYTE-11 marks the end of the second phase of FORCYTE develop-

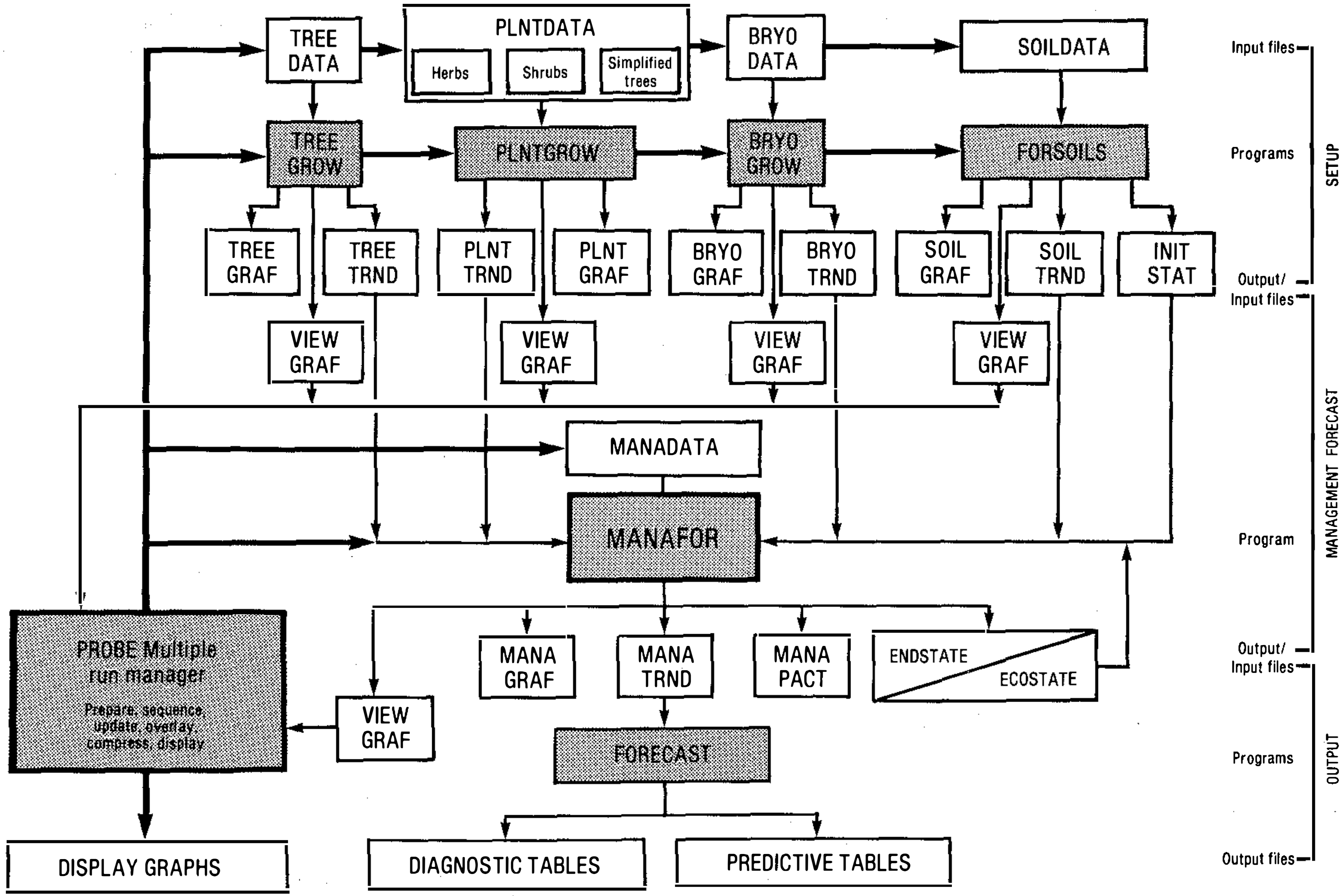

Figure 1. The overall file and program structure of the FORCYTE-11 modeling framework. Users can assemble the appropriate set-up modules to produce a simulation of any particular forest or agroforestry ecosystem. The relationship between the PROBE supervisory software and the FORCYTE framework can be seen.

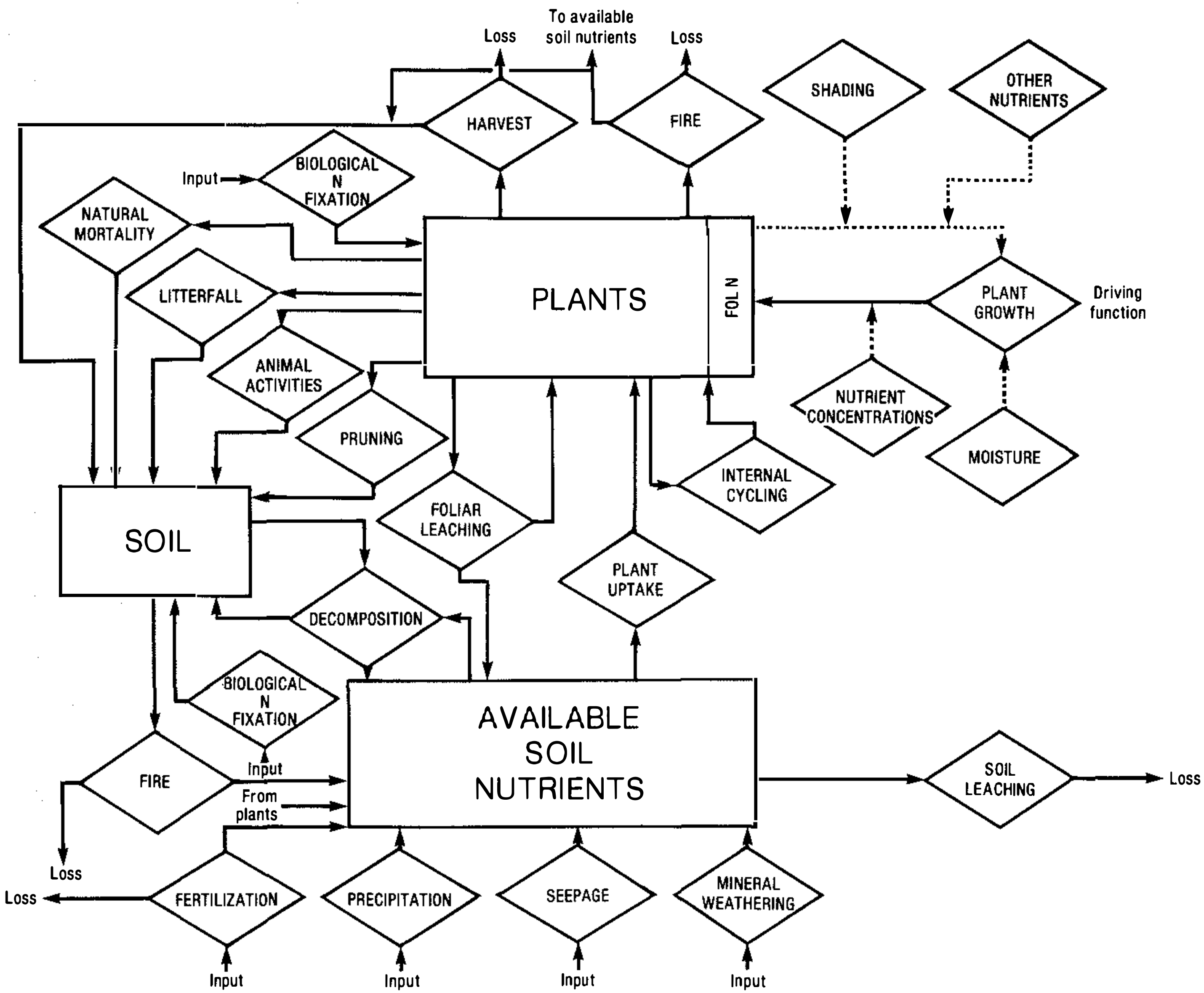

Figure 2. Major compartments and processes that are operational in the benchmark version of FORCYTE-11. Some of the processes shown in earlier published versions of this diagram are not available in this benchmark version but are expected to be available in future versions.

Table I. Simulated options and processes represented in FORCYTE 11

A. Management options available

- Site preparation—manual weeding, broadcast slashburning
- Regeneration—planting, natural seeding, vegetative reproduction (root suckering or coppice sprouting); regeneration of single or multiple-species crops
- Weed control—manual
- Stocking control—precommercial thinning (spacing)
- Nurser crops—Nitrogen-fixing herbs, shrubs, or trees
- Stand maintenance—control of noncrop species
  —control of species composition
- Fertilization—single or multiple nutrients
- Commercial thinning—high, low, or row thinning. Any utilization level
- Final harvest—clearcutting, shelterwood, or seed tree method (the model can simulate multi-age, selection cut stands, but not as well as its simulation of even-aged clearcut systems) with any utilization level
- Utilization level—stem only, whole tree (above ground), or complete tree (above- plus below-ground), or any intermediate level

B. Natural disturbance events that can be simulated

- Wildfire—effects of wildfire on ecosystem organic matter and nutrients
- Herbivory—insect defoliation of canopies, wildlife browsing of seedlings, domestic livestock grazing of competing vegetation.

C. Processes that can be simulated

- Photosynthesis and foliage nitrogen efficiency
- Plant growth and biomass accumulation
- Nutrient limitation of growth
- Litterfall, above-ground and below-ground
- Foliar leaching
- Plant competition for light and nutrients
- Effects of shading on photosynthesis—sun and shade foliage
- Effect of shading on height growth
- Plant mortality—density-dependent mortality (stand self-thinning, or shading by competitors) and density-independent mortality
- Winter photosynthesis—evergreen photosynthesis when deciduous competitors are leafless
- Geochemical cycle—inputs and outputs of nutrients to and from the ecosystem: precipitation, weathering, nitrogen fixation, fertilization, soil leaching, harvest removals
- Biogeochemical cycle—uptake, litter fall, foliar leaching, decomposition (mineralization/immobilization).
- Internal cycling—retranslocation of nutrients at the time of tissue senescence
- Decomposition—loss of organic matter and mineralization and immobilization
- Effect of clearcutting on decomposition
- Soil leaching
- Soil exchange capacities

ment, as FORCYTE-10 was the end of the initial period of development. As time and resources permit, a number of further developments are planned.

1. The benchmark FORCYTE-11 will be extended to add a variety of new capabilities. These will include an explicit representation of temperature and moisture in the simulation to permit the model to be used for climate change research and yield prediction. Mechanical site preparation (piling or windrowing, with or without burning), erosion, compaction, phosphorus sorption-desorption, soil mixing by animals or mechanically, some degree of horizontal spatial representation, and a simulation of canopy shape will be added. This model will be called FORCCAST (FORestry and Climate Change ASsessmenT).

2. A variety of improvements will be made to FORCYTE-11 to render it suitable for use in either tropical or temperate agroforestry or in agriculture. The resulting model will be called AGRICYTE (AGRICultural Yield Trend Evaluator).

3. FORCYTE-11 will be modified to make it more suitable for use in mined land reclamation research and the model will be called MINESYTE (MINed EcoSYstem Trend Evaluator). The planned modifications could render the model more useful for acid rain and air pollution research applications.

4. Development of user-friendly, animated color microcomputer games based on one or more of the above models is planned. The intention is to produce these at several levels to serve various purposes:

   a. The high school version will communicate ideas of resource management and environmental sustainability in grade 11 and 12 high school courses. It will also be used for public hearings, openhouses, and other public education applications.

   b. The college-university version will be used for undergraduate teaching in resource ecology or management courses.

   c. The graduate-professional version will be for use in research or as a professional management decision support tool.

All these developments are dependent on securing the necessary research grant support. Other anticipated future activities include the linkage of FORCYTE or other models with a GIS system to change from stand-level to regional prediction and the use of a regional or national modeling framework to permit the model(s) to be used to assess the contribution of Canadian forestry to the greenhouse problem via a national forestry carbon budget analysis.

CONCLUSIONS

Although the capabilities of FORCYTE have developed far beyond the scope of the original project, the objective of the model has not changed: to be able to make short-, medium-, and long-term predictions concerning the yield, sustainability of yield, economics, and energy efficiency of a wide range of alternative management strategies.

Initially a mainframe model, FORCYTE now runs on 386-level microcomputers thanks to the enormous progress made in microcomputer hardware. Until recently, the model's computer requirements were increasing at about the same speed as microcomputer hardware technology, which therefore limited modeling strategy. The hardware developments of 1988 and 1989 have leaped ahead of the model, and it is now anticipated that by 1990 a fairly standard personal computer will be fully capable of running any of the existing or planned model versions.

A model is only as good as its performance and ease of use. Major improvements have been made in the latter by the development of the PROBE package of software (Fig. 1), and further development in this area is anticipated. Verification and validation projects are planned, and a group of cooperators willing to field test the benchmark version of FORCYTE-11 has been identified. A report on the results of this activity is planned for 1990 and 1991.

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TIMBER SUPPLY ANALYSIS IN THE ALBERTA FOREST SERVICE

D.A. Price and E.M. Wrangler
Alberta Forest Service
Edmonton, Alberta

INTRODUCTION

The forest lands of Alberta cover an area of approximately 350 000 km^2 and occupy approximately 60% of the total area of the province. For the most part these lands are Crown owned and are administered primarily by the Alberta Department of Forestry, Lands and Wildlife.

Alberta's recently completed forest inventory indicates the total volume of timber on Crown lands to be 2.4 billion m^3. Approximately 60% of this volume is softwood, mainly white and black spruce and lodgepole pine, and 40% is hardwood, mainly aspen and balsam poplar. The calculated coniferous annual allowable cut (AAC) from Alberta's existing growing stock is 14.8 million m^3. The deciduous AAC is 11.6 million m^3 and is primarily aspen.

CURRENT SITUATION

The use of computer models has enabled the Alberta Forest Service (AFS) to evaluate the provincial timber supply and provide good estimates of volumes available for development after all commitments were met in the 1986 quota renewal program. The several new major forestry developments focused primarily on the provincial deciduous resource, but coniferous resource was also allocated.

What role have computer models played?

The magnitude of assessing provincial timber supplies is such that computers assist with much of the data sorting, retrieval, and subsequent manipulation and computation. Computers do not replace human decision making.

The AFS has several computer systems, which can be considered individual components of a larger system that monitors provincial wood supply. These systems assist with strategic and operational planning and program monitoring.

The Phase 3 provincial forest inventory is stored and maintained in the Alberta forest inventory, storage, and maintenance system, commonly known as AFORISM. This system is periodically updated to reflect changes in the forest land base, including depletion activity (harvesting, natural catastrophe), silviculture, enhancement (better definition of species), error correction (interpretation or computer coding), and administrative changes (land status and administrative boundaries). The system is on a mainframe due to its size.

Systems known as CRUZCOMP and TREEMEAS utilize tree section data, Phase 3 inventory, and cruise plots to produce volume information that is linked to AFORISM cover types in the form of cover type volume tables and merchantability factors. These systems operate on the mainframe.

The relationships developed from the tree section data and the permanent sample plot data (PSP system) are utilized for developing yield tables, site productivity, mortality, and ingrowth. Electric Data Collectors (EDC) are used to collect permanent sample plot data, which are transferred via microcomputer to the mainframe files.

A second major component along with AFORISM in actual wood supply analysis is the Timber Management Planning System or TIMPLAN. This system deals with the long-term planning aspects or determination of sustainable long-term timber supplies. This system runs on the mainframe.

Within the TIMPLAN system, the timber land base contributing to the annual allowable cut is defined by a variety of methods. First, a subset of AFORISM data for the described administrative unit such as a Forest Management Unit (FMU) is obtained. A variety of merchantability criteria, subjective land base deletion criteria, and ground rule deletions are applied against this subset to define a net land base.

What does this mean? Coniferous stands must meet a minimum volume requirement (m^3/ha) based on a given utilization standard by a specified maximum age in order to be deemed merchantable. Using the management planning system, each stand volume is compared to the Volume Sample Region

(VSR) conifer fully stocked yield curve to determine merchantability status. If the overstory stand does not meet the minimum coniferous volume requirement, the understory is tested. If neither meets the requirement, the stand is considered never merchantable and excluded from the conifer land base. Stands not meeting the minimum conifer volume requirement are analyzed for merchantability to deciduous standards.

After the management system is run, subjective land base deletions are made to remove additional stands considered by field personnel to be never merchantable. Examples include density-height cover type combinations with commercialism, species, or origin concerns; areas tentatively slated for resource use not consistent with timber production (agriculture expansion); and stands with larch as the primary or secondary species.

The land base is further reduced through information gathered in the Integrated Resource Plan (IRP) process and land-use referrals. Concerned land management agencies identify items of concern that effectively reduce the timber land base available for timber management and concerns that would limit timber harvesting by the imposition of restrictive conditions. All proposed land base deletions are illustrated on maps for measurement and coding.

Standard exclusions to the land base are slopes exceeding 45%, inaccessible and inoperable areas, and areas not under AFS mandate. The computer file to this point contains the net merchantable land base.

Ground rule deletion information is compiled and mapped. This includes 1) area removals such as ecologically significant areas, recreation areas, grazing reserves, and buffer widths greater than 200 m; 2) 100% lineal removals such as major rivers, lakes, highways, or other features not occurring regularly throughout the FMU having a buffer width (up to 200 m) applied to a lineal measurement of the feature; and 3) sample-area removals such as lineal features occurring regularly across the FMU such that measurement on a sample basis will give an accurate estimate of the total area removed. Buffer widths are applied.

Once this information is mapped, it is measured and coded using the TIMDEL system, which consists of a microcomputer, digitizing table, printer, and software. This information is transferred to the mainframe and applied to the computer file containing the net merchantable land base to produce the land base used in AAC calculation. This land base is in the form of timber classes and corresponding areas. Area weighted yield curves for each type of timber class and an average curve are produced. Now all the basic data needed to calculate an AAC exist.

A combination of an Area-Volume (A-V) check and a Timber RAM supply analysis are conducted. The A-V check is run on the mainframe or microcomputer and is used as the seed for the Timber RAM AAC. The A-V check is an iterative process using an estimated AAC and a specified rotation. Timber RAM is a linear programming optimization model that is capable of dealing with multiple constraints. It is run strictly on the mainframe due to time requirements and size of the problem. With both analyses, a set of guidelines for the establishment of long-term supply levels are followed and include rotation length and volume flow patterns, as examples.

At this point an anticipated fire loss reduction is applied as a volume deletion to the AAC.

The results from this analysis are compiled, a recommended AAC is sent to senior management with appropriate back-up data, and an approved AAC is returned to the analysis team for use in the next planning stage.

Short-term planning is the process of determining spheres of interest containing approximately 20 years of AAC and sequencing this for each coniferous and deciduous quota holder and Miscellaneous Timber Use (MTU) area in the FMU. Surplus timber is identified at this step, which is also referred to as the third stage of AFORISM.

There are general guidelines to follow in harvest sequencing while maintaining an awareness of operational realities. Existing infrastructure and road networks are considered. Wherever possible, distinct physiographic features are used as natural boundaries for each quota sphere or cut plan area to minimize physical barriers to log transportation.

Other priorities include timber maturity and condition, existing dispositions pending completion, reserve blocks scheduled for harvest once criteria for removal are satisfied, and recognition of existing operating areas wherever possible.

Twenty-year volumes are calculated for each disposition, and maps are colored according to origins of harvest based on the first 20-year wood supply at 50% removal. The colored stands indicate the spatial distribution of the stands available to harvest. Quota spheres are described and the volume is tallied within each sphere. As well, each sphere is generally divided into four cut-plan areas, each containing approximately 5 years of timber volume at 50% removal. The third stage of AFORISM summarizes the volume by cut-plan area and by average volume and area and weighted average age.

A major premise of the timber supply analysis is the successful regeneration of all cutovers and the implementation of proposed intensive silvicultural practices. Areas that require silvicultural attention are identified through the timber supply analysis and are referred to the Reforestation and Reclamation Branch for possible silvicultural prescription.

Computer modeling of responses to treatments can be used to evaluate potential treatments, and further modeling can evaluate potential AAC impact to help define program directions.

Computer models are used throughout program delivery and monitoring as well. For example, in areas with visual sensitivity, the AFS uses Digital Terrain Modeling (DTM) in evaluating block layout. The AFS has also provided assistance to some Forest Management Agreement (FMA) holders in visual evaluations. The DTM is run on a microcomputer and is part of a complete geographic information system (GIS). Data from AFORISM can be transferred to floppy disk, as can cruise information, to serve as a data base for modeling. This flexibility enables operational planners to delete, for example, slopes exceeding operational limitations, before modeling the block layout.

To assist field staff with delivering the program, a version of CRUZCOMP, MicroCRUZ for microcomputers has been developed. Also, AFORISM data subsets have been provided to field staff for use on their microcomputers.

In the monitoring aspects computer systems are again important. The TREES system, which is a mainframe system, maintains, for example, all administrative and related assessment information on dispositions; production records, including scaling, audit, and movement of timber; annual operating plan information including operations inspections, and mill inspections. All of this information can be summarized in a variety of ways and is used, for example, when strategic planning for the next year's workload is carried out.

Electric data collectors are used when check scaling is carried out, and the information can be fed via microcomputer into the TREES system when personnel return to head office. Scaling information is passed from companies to the AFS via floppy disk or modem.

All of these uses of computers and computing systems are important components in the wood supply analysis done by the Alberta Forest Service (Fig. 1).

THE FUTURE

What's next? Inventory and map update will be helped greatly by GIS, which in turn will ensure information is available for further analysis in AAC impact assessment on a timely basis. Evaluation of operational impacts such as buffer width adjustment and plot locations should be easier with GIS as a tool. Presentations requiring visual aids such as maps highlighting spatial location will be faster to prepare.

The AFS is interested in working with the forest industry in Alberta to develop a GIS. We worked together on log scaling, and the end result was a common procedure and a standard data base. The AFS hopes for similar results in the GIS initiatives.

Microcomputers are going to speed the auditors' work as the links with TREES will provide needed base data before audits are carried out. As well, statements will be prepared faster after audits are complete through standardized formats that auditors, rather than support staff, will prepare.

Electric data collectors will be used to streamline and decrease errors, allowing transfer to cruise information to the microcomputers for analysis in MicroCRUZ. Elimination of the tally sheet and key punch step will increase efficiency and expedite data processing at the field level.

CONCLUSION

The use of computers and modeling capabilities will increase and evolve as time passes. Timber supply analysis in the AFS will remain dynamic and progressive with the support of computers.

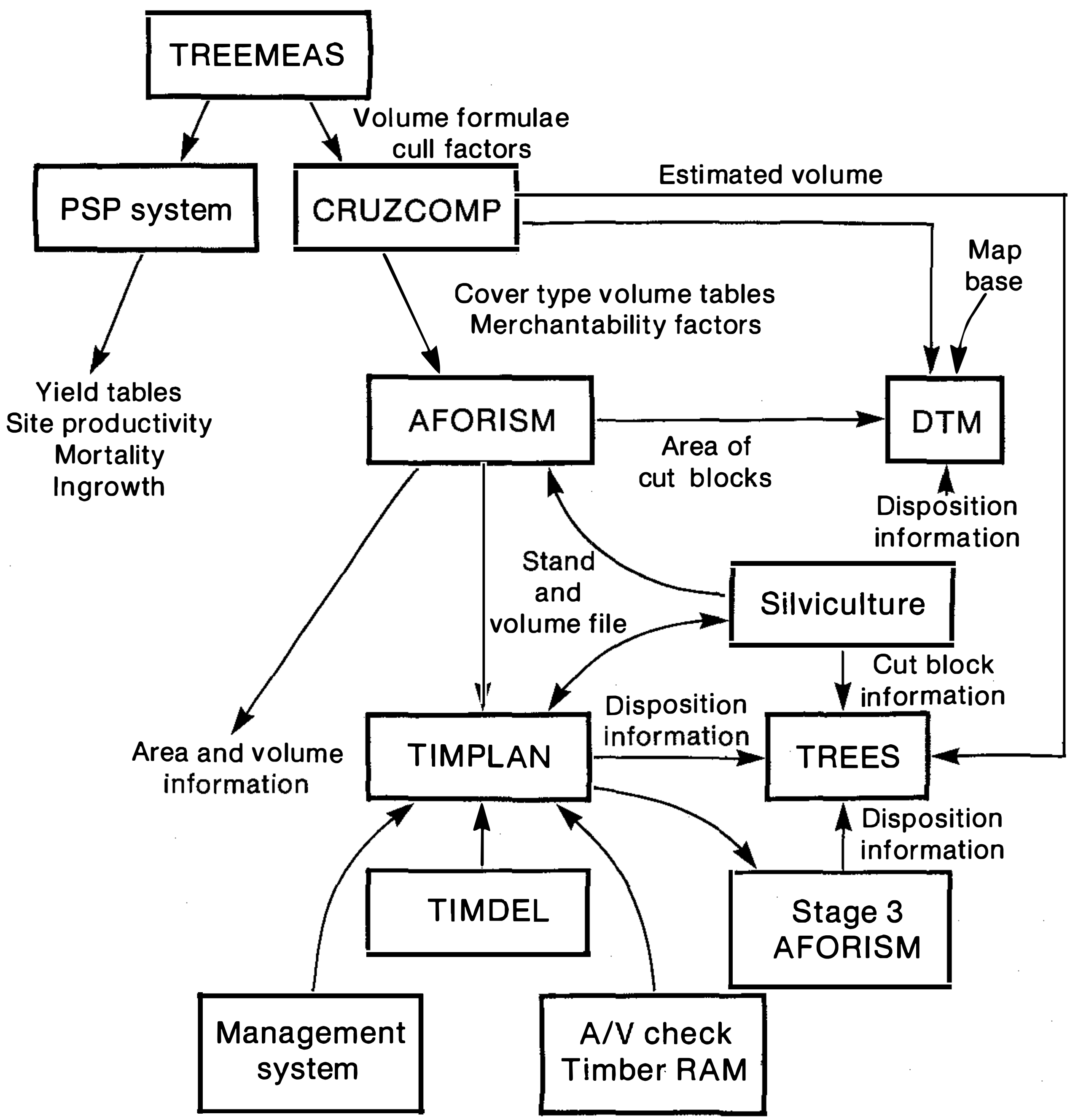

Figure 1. Alberta Forest Service wood supply analysis computing system.

WOOD SUPPLY ANALYSIS AT WELDWOOD—HINTON

H.D. Walker
Weldwood of Canada Limited (Hinton Division)
Hinton, Alberta

ABSTRACT

Weldwood of Canada Limited (Hinton Division) manages about 1 million ha of public forest near Hinton. The forest is divided into five working circles, which are stratified into 135 operating compartments. Each compartment is being further stratified into integrated resource planning strata. A set of allowable harvesting, renewal, and tending tactics are identified for the various timber types and integrated resource planning strata. Company staff queue compartments for operations according to average age, location, and operational concerns. This information, along with company inventory and yield data, is used within the ATAMO wood supply model to design alternative timber management strategies. This model allows trial harvest, renewal, and tending priorities and levels to be projected over time, thus illustrating the long-term, forest-level consequences of alternative strategies. This approach to wood supply analysis allows Weldwood staff to design timber management strategies that reflect company objectives while enhancing public forest values.

INTRODUCTION

Weldwood of Canada Limited (Hinton Division) manages, under agreement with the Province of Alberta, about 1 million ha of public forest near Hinton, Alberta (Fig. 1). The forest supplies coniferous fiber for a 209 000 air-dried metric tonnes per year of bleached kraft pulp mill consuming 1 million m^3/yr and a 75 million fbm/yr stud mill consuming 350 000 m^3/yr. Expanded sawmill and pulp mill facilities are being constructed, which will increase coniferous consumption, including purchased wood, to about 2.8 million m^3/yr. About 57 000 m^3/yr of aspen are also harvested and sold to others, and Weldwood has a limited-term option to utilize deciduous timber itself.

Under the terms of a Forest Management Agreement (FMA) signed in June 1988 between the Government of Alberta and Weldwood of Canada Limited (Order in Council 290/88), a preliminary Forest Management Plan (FMP) is due to the province by 15 June 1989, and a detailed FMP is due 15 June 1991. The FMA allows the company to design forest management strategies to meet current and projected mill demands within a sustained-yield context while maintaining or enhancing other renewable resource values on the forest. Forest management planning takes place within a hierarchy of plans and policies for land use and integrated management. Weldwood FMPs are primary implementing documents for the timber and wildlife-habitat components of provincial subregional Integrated Resource Plans (Alberta Energy and Natural Resources 1984; Alberta Forestry, Lands and Wildlife 1988). Areas not designated for other prime uses by Integrated Resource Plans have a prime use for the growth and harvest of timber, subject to limitations set out in the FMA. In addition to the FMP, which has a planning horizon of 80-100 years and 5-year cut-control periods, the company prepares an Annual Operating Plan (AOP), which has a 2-year planning horizon and shows planned operations by season for individual cutblocks.

This paper describes the approach used within the forest management planning process to analyze wood supplies over time. The company's current forest management system is briefly described, as are the data used for supply analysis. The wood supply model being developed to analyze wood supplies and design timber management strategies is then described.

THE CURRENT FOREST MANAGEMENT SYSTEM

Weldwood's forest is divided into five working circles (Athabasca, Marlboro, Embarras, McLeod,

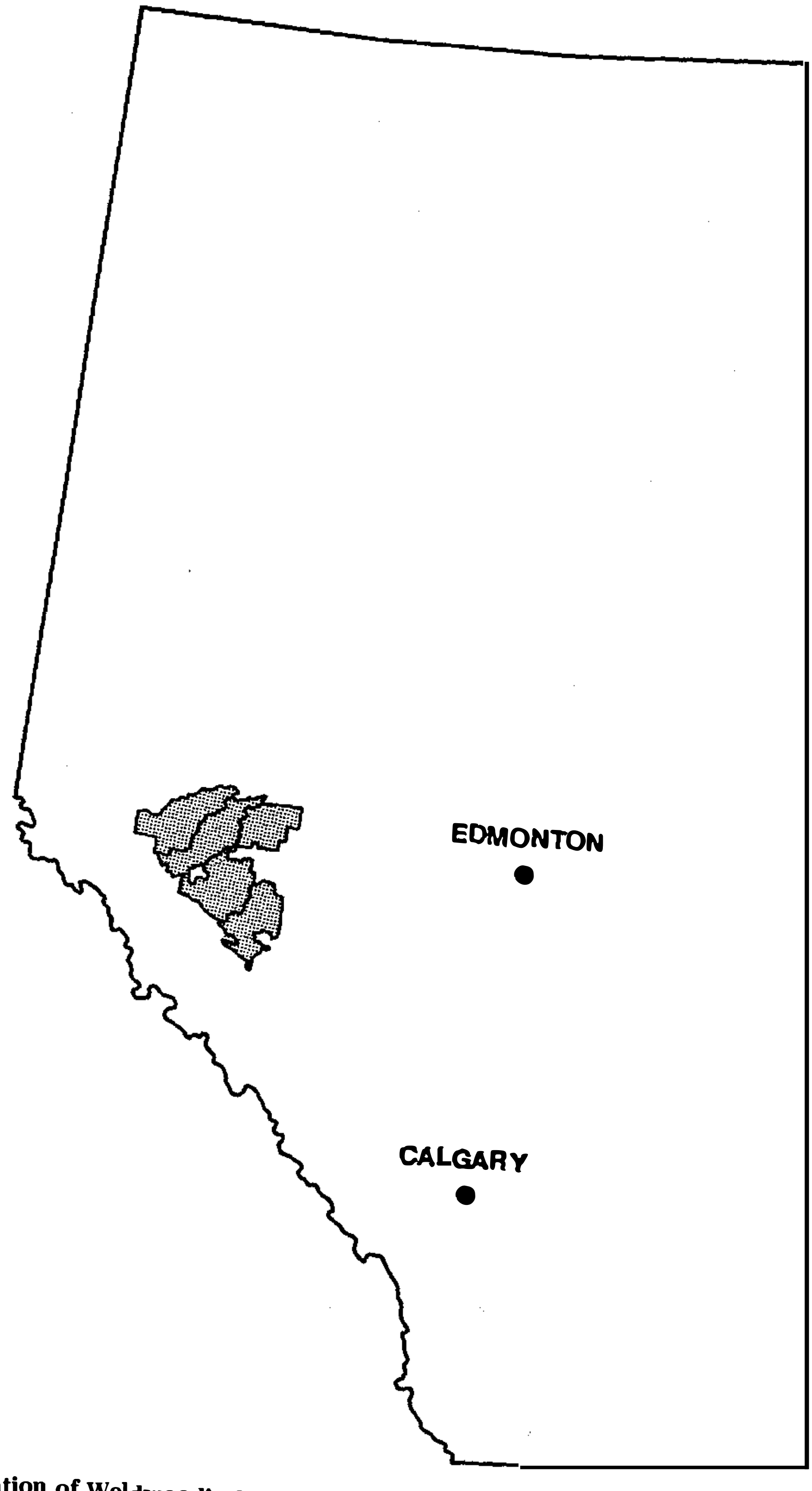

Figure I. Location of Weldwood's forest management area within Alberta.

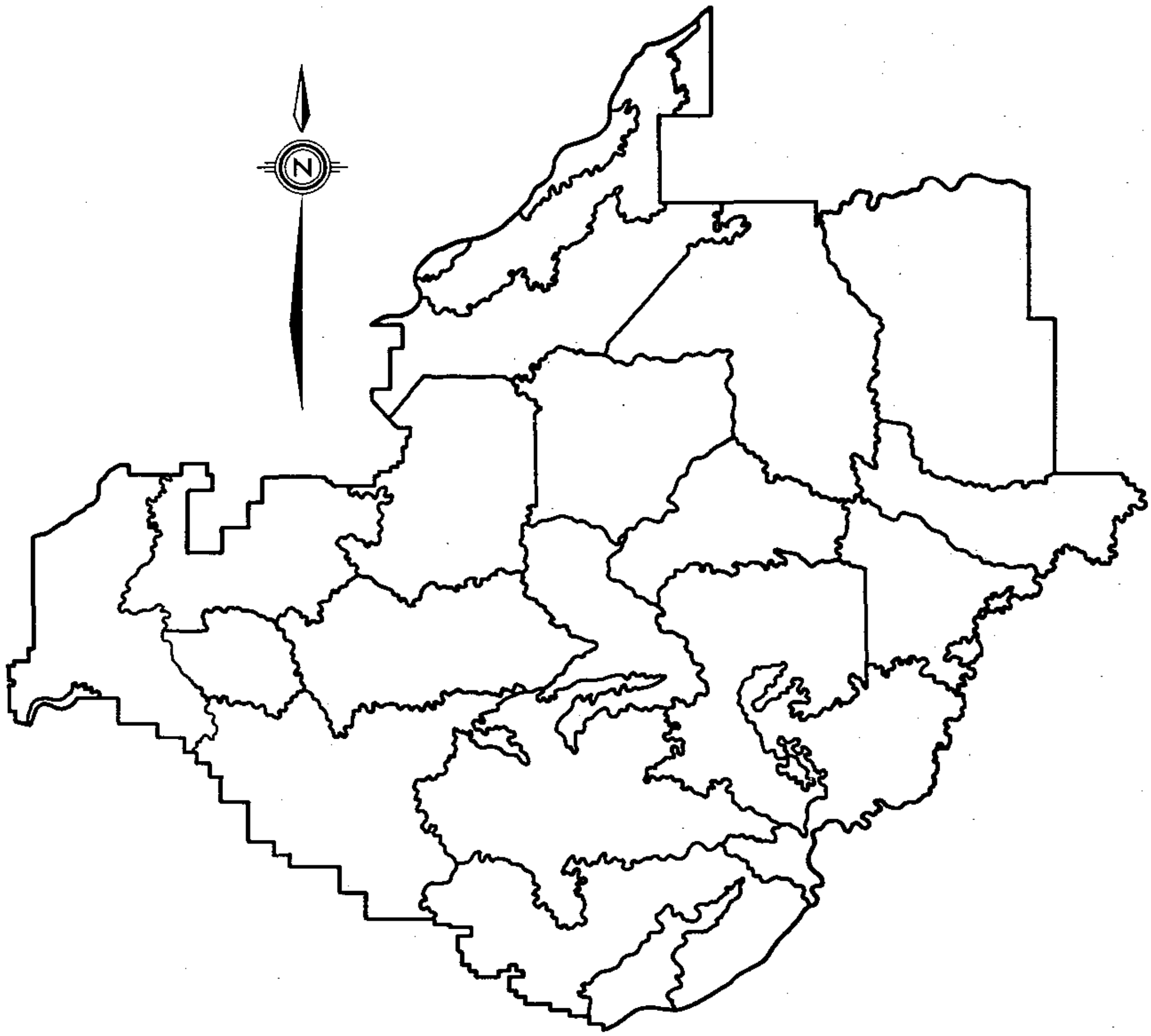

Figure 2. Compartments within the McLeod working circle.

and Berland), each of which is considered to be a separate management unit. The working circles are further subdivided into 135 operating compartments (Fig. 2). Compartment boundaries are determined by the average age of stands within the compartment and by operational considerations. Each compartment will be subdivided into Integrated Resource Planning (IRP) strata. For each IRP stratum, allowable harvesting and silvicultural tactics are being developed that are designed to facilitate timber management while considering other resource values.

Harvest Sequencing

Compartments within each working circle are queued for operations according to average age, subjective risk assessment, distance from Hinton, stand composition, access, and mill requirements. In general, older and higher-risk compartments are opened first. This is balanced by a desire to maintain approximately constant average haul distances over time (currently about 64 km), a need to maintain an orderly road construction program, and evolving mill requirements. Once a compartment has been opened, harvesting and renewal of all operable stands within the compartment progresses as quickly as practicable within operational constraints, mill requirements, operating ground rules, and multiple-use concerns. This preserves uniformity of stand ages for future harvests within compartments. After all operable stands in a compartment have been harvested and renewed, it is closed.

Harvesting takes place in two passes, where about one-half of the operable area of a compartment is clearcut with each pass. In practice, about one-third of the total compartment area is harvested with each pass. The remaining third is not harvested because it is nonforest, riparian strip, critical wildlife habitat, or otherwise inoperable. Second passes are removed about 10-20 years after first passes, after regenerating stands from first-pass cuts have achieved an average dominant height of 2 m.

Silviculture

Silviculture tactics are designed to maintain or enhance the long-term growth and vigor of timber in the forest. The variety of cutting, regeneration, and tending methods used to promptly return cutovers to healthy young stands are described in the FMP. The company owns the timber resources on the forest, and the Province of Alberta, in contrast with most other provinces, has an excellent track record of preserving tenure stability. This stability is critical for Weldwood to consider discretionary investments in intensive management.

Forest Inventory

The basic management inventory system is the Photo Point Sample (PPS). About 7500 points uniformly distributed across the forest are used to estimate cover type, density, and height class distributions. Each photo point represents about 133 ha of forest. When combined with age information from our fire-origin maps, site index information for each point may also be derived. The PPS data are used for deriving age-class distributions for each working circle, which are being augmented by digital orthophoto maps for compartments expected to be operated in the next 20-30 years. A system is also being designed to collect inventory data on the 100 000 ha of managed stands harvested since Weldwood began operation in 1956.

Growth and Yield

Weldwood maintains a Permanent Growth Sample (PGS) system of about 3000 permanent plots for deriving local growth and yield information. These plots are on a geometric grid across the forest, with additional special clusters established to increase sample size in some types. Most plots are revisited about every 10 years, and many have been measured three times. The data from these plots form the basis of the company's aerial stand volume tables (W.R. Dempster and Associates Ltd. 1985) and tree and log profile forecasting system (W.R. Dempster and Associates Ltd. 1988). Based upon the PGS data, a set of 11 broad type classes have been derived (Table 1).

Table 1. Type class distribution within the forest

Type class	Description	% of forest
1	Lodgepole pine	33
2	Lodgepole pine and other softwoods	18
3	Lodgepole pine and hardwoods	7
4	White spruce	3
5	White spruce and other softwoods	6
6	White spruce and hardwoods	2
7	Black spruce	2
8	Black spruce and other softwoods	2
9	Sub-alpine fir and other softwoods	1
10	Hardwoods and softwoods	5
11	Hardwoods	4
Other	Nonproductive	17
Total		100

Up to four density classes have been defined within each type. Within the 30 resulting yield classes, stand volumes are expressed as a function of either weighted average height or top height (average height of the 100 largest-diameter trees per hectare). Where appropriate, both coniferous and deciduous volumes are reported for each yield class.

TIMBER SUPPLY MODEL

The purpose of timber supply analysis at Weldwood is to identify the forest's capacity to produce sustainable volumes of timber at reasonable costs and in the correct product and species mixes. For any harvest pattern over time, a timber management strategy is implied that must be followed for the chosen pattern to be realized. This strategy represents the company's chosen compromise among its objectives, within available harvesting, regeneration, and tending tactics, and within the constraints associated with owning timber resources on public land.

Figure 3 shows the process used to derive the strategy. Inventory and yield data discussed above define the initial forest structure, and constraints arising from the FMA and operating ground rules help define acceptable harvesting, regeneration, and tending tactics. Weldwood's objectives and constraints are the basis of strategic alternatives regarding harvest sequences and harvest and regeneration rates. This information is used within a wood supply model for designing and evaluating timber management strategies.

Model Structure

For the previous management plan, the Forest Yield Projection System (FYPS) (W.R. Dempster and Associates 1986) was used to perform a modified area-volume check calculation of annual allowable cut (AAC) as required by the Alberta Forest Service (Alberta Energy and Natural Resources 1985). Although FYPS did a good job of analyzing the forest's capacity to produce fiber over a chosen "rotation" period, regenerated yields from stands projected to be cut in the future could not be incorporated into the analysis. This precluded using the model to identify the forest's capacity to produce timber on a sustainable basis. More importantly, FYPS did not allow Allowable Cut Effects (ACEs) from future discretionary silvicultural investments to be considered when establishing present harvest levels.

The ATAMO (And Then A Miracle Occurs; see Acknowledgments) model being developed is designed to overcome these difficulties while retaining a modified area-volume-check structure. This model projects forest development over time in response to user-defined tactics for harvesting, regeneration, and tending (Fig. 4). Model philosophy is similar to that of FORMAN (Wang et al. 1987), although ATAMO was developed especially to reflect the FMA–working circle–compartment hierarchy of boundaries and the two-pass harvest system used by Weldwood. The ATAMO model is a simulation model with a Model II structure (Johnson and Scheurman 1977). This allows for great flexibility in defining alternative silvicultural regimes within a problem size small enough to run readily on a microcomputer.

The ATAMO model is used to design strategies on a working-circle basis. Management strategies are defined for a 160-year planning horizon in 5-year planning intervals. The planning interval length coincides with required cut-control periods, and the planning horizon length allows estimates of long-run sustainable yields to be made.

Model Requirements

Forest structure is initially defined as age-class distributions (stand classes) within yield classes, where yield classes are groups of stands with similar species mix, site index, and density. For each yield class, operable age ranges and three age-driven yield curves are defined (softwood volume, hardwood volume, and sawlog percentage of softwood volume). The age-driven volume curves are transformations of the height-driven aerial stand volume tables, and the sawlog percentage of softwood volume curves are derived using the tree and log profile forecasting system. To preserve the basic height-driven nature of the yield curves, 3-m site index classes are defined within each of the original volume tables. This results in the definition of nearly 200 yield classes.

Area, age, present yield class, extensive regeneration yield class, intensive regeneration yield class, intensive regeneration priority, and compartment are identified for each stand class. Extensive regeneration yield classes are those assumed when minimum legal regeneration standards are implemented after clear-cut harvest. Intensive regeneration yield classes are those assumed when discretionary investments in intensive silviculture are made after clear-

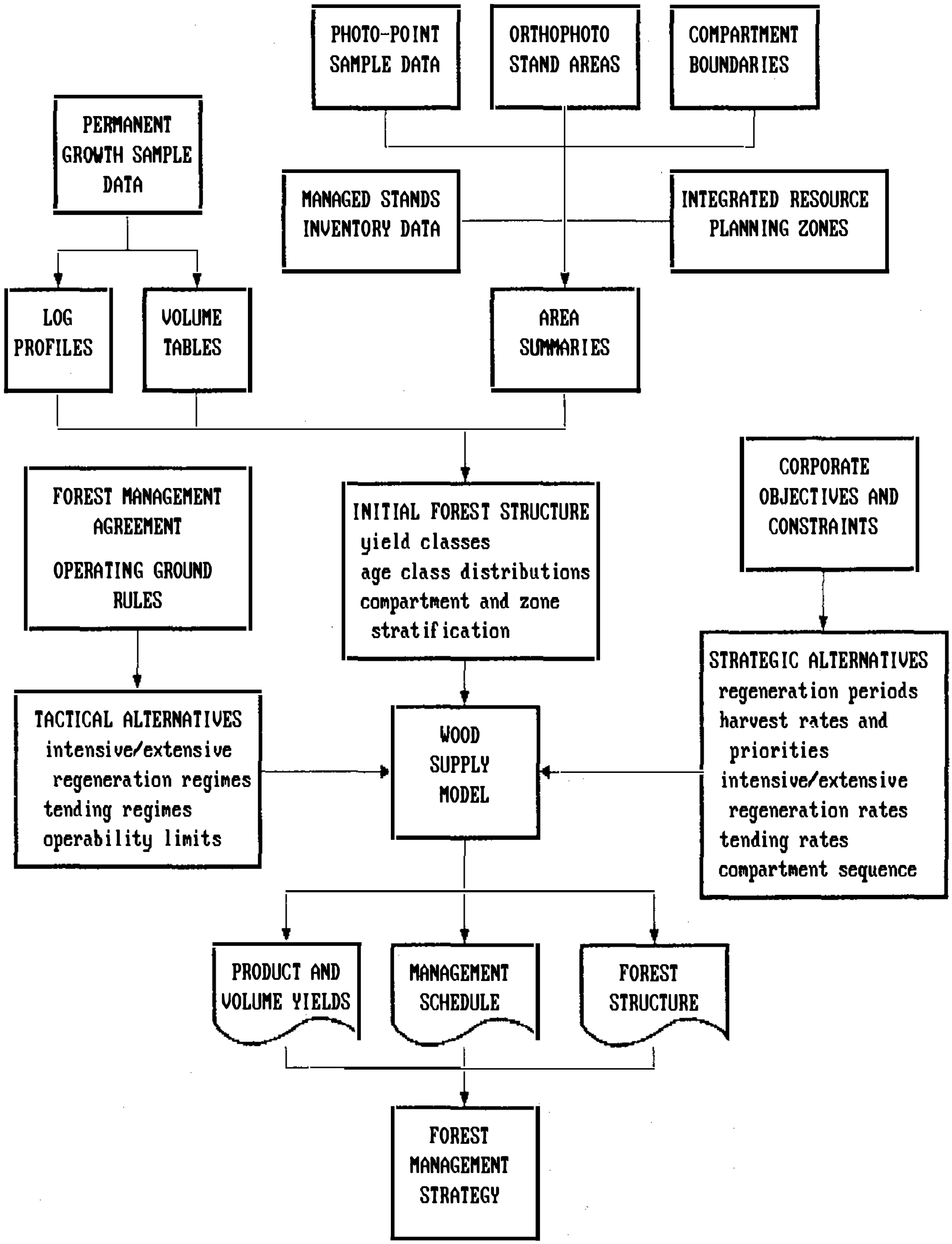

Figure 3. Forest management strategy design.

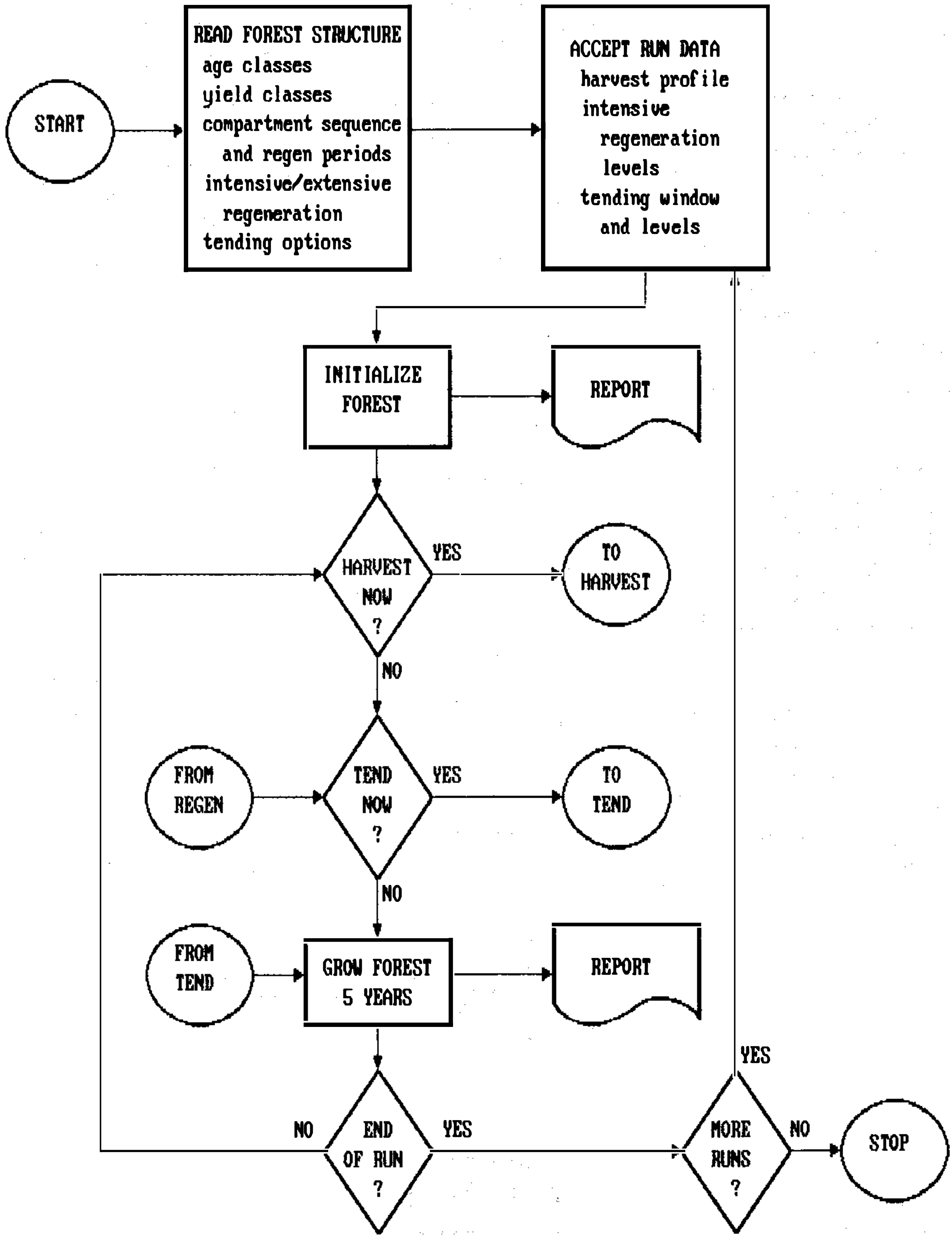

Figure 4. ATAMO main program.

cut harvest. The intensive regeneration priority reflects stand-level priorities for allocating discretionary silviculture investment dollars. The yield classes used when stands are tended are also identified.

In addition to the basic forest structure data, ATAMO requires a compartment sequence and profiles of desired levels of harvesting, intensive regeneration, and tending over time. These define the management strategy for one model run.

Model Operation

Within each 5-year step of a run, harvests are taken from open compartments in the specified sequence (Fig. 5). The model first checks for available volume, which is operable volume from stand classes within an open compartment where harvests from this pass may now be taken. Harvests are then taken from the oldest available stand classes in the longest-open compartments until either all available volume has been harvested or the desired harvest level has been reached. New compartments are opened as necessary and are closed when all available second-pass stand classes have been cut.

Following harvest, cutovers are regenerated (Fig. 6), eligible stand classes are tended as desired (Fig. 7), and the resulting forest is grown for 5 years. Statistics on forest structure are collected and reported at each planning interval. When the planning horizon is reached, a new management strategy may be specified and the process repeated (Fig. 4). Through an iterative process involving many runs, the preferred timber management strategy is developed.

DISCUSSION

The ATAMO model offers substantial improvements to area-volume check allowable-cut approaches currently used in Alberta. Most importantly, the model lets our staff easily test alternative management strategies including harvest rates, management schedules, and regeneration and tending tactics and priorities. Strategies are assessed in terms of the flows of species volumes, costs, and products over time, and the evolving forest structure. By avoiding optimization structures, model size is small, transparency is maintained, and users must make many runs when designing the strategy that offers the best compromise among competing objectives. This forces users to develop a good understanding of local forest dynamics.

Rotations

The ATAMO model, in contrast to conventional area-volume checks, does not require rotations to be specified. The model cuts stands at the ages when they are highest priority for harvest relative to other operable stands in the management unit. The model does not assume that there is an optimal age at which stands should be harvested, regardless of the forest in which stands exist (a classical stand-level notion of rotation). Nor does it assume that the optimal length of time in which the current forest should be liquidated is the average mean-annual-increment-maximizing age of stands within the forest, regardless of both the age-class structure of the forest and ACEs from alternative silvicultural investments (a classical forest-level notion of rotation or of conversion period). Both concepts of rotation preclude attaining maximum benefits from the forest over time if the current forest structure is not uniform and if nondeclining yields are important.

Within ATAMO, both stand-level and forest-level rotations may be determined but as outputs rather than inputs. The stand-level rotation is the average age of harvested stands, and the forest-level rotation is the time required to cut over once all compartments in the working circle. Because age classes and yield classes in any Alberta forest are not uniformly distributed, these two rotations are quite different. In ATAMO, the harvest-maximizing forest-level rotation is the time required to cut all compartments in the working circle while harvesting the maximum sustainable level.

ATAMO provides a forest-level means to evaluate investments in intensive silviculture. As these investments are made, plantations have higher yields and become operable at an earlier age, and the existing forest can be harvested faster. The trade-offs between higher silvicultural costs and lower harvests may be explicitly examined.

Figure 8 illustrates these concepts. The conventional area-volume check method determines the harvest level that will exactly harvest all growing stock in the current forest over some rotation period

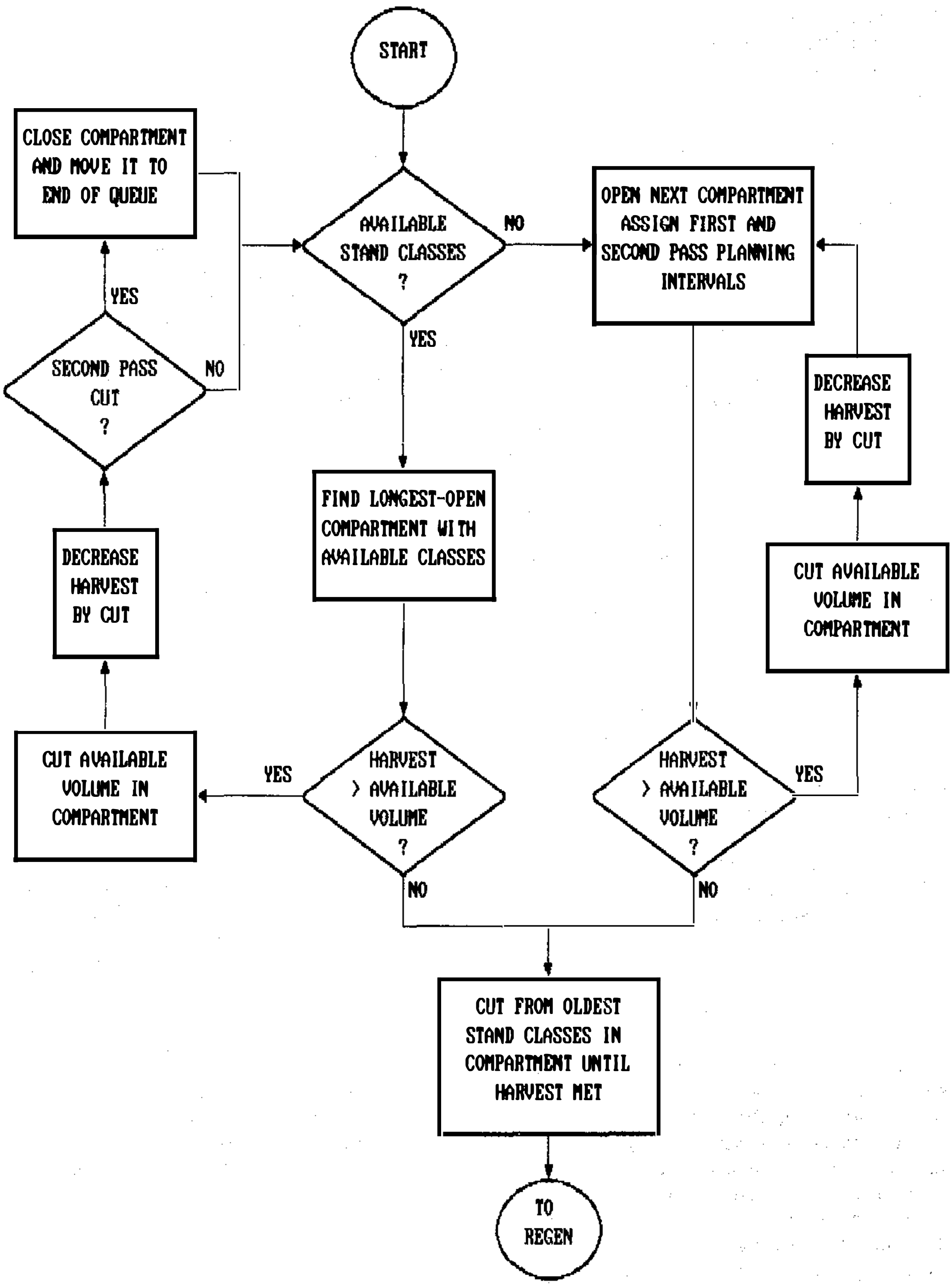

Figure 5. ATAMO harvest subroutine.

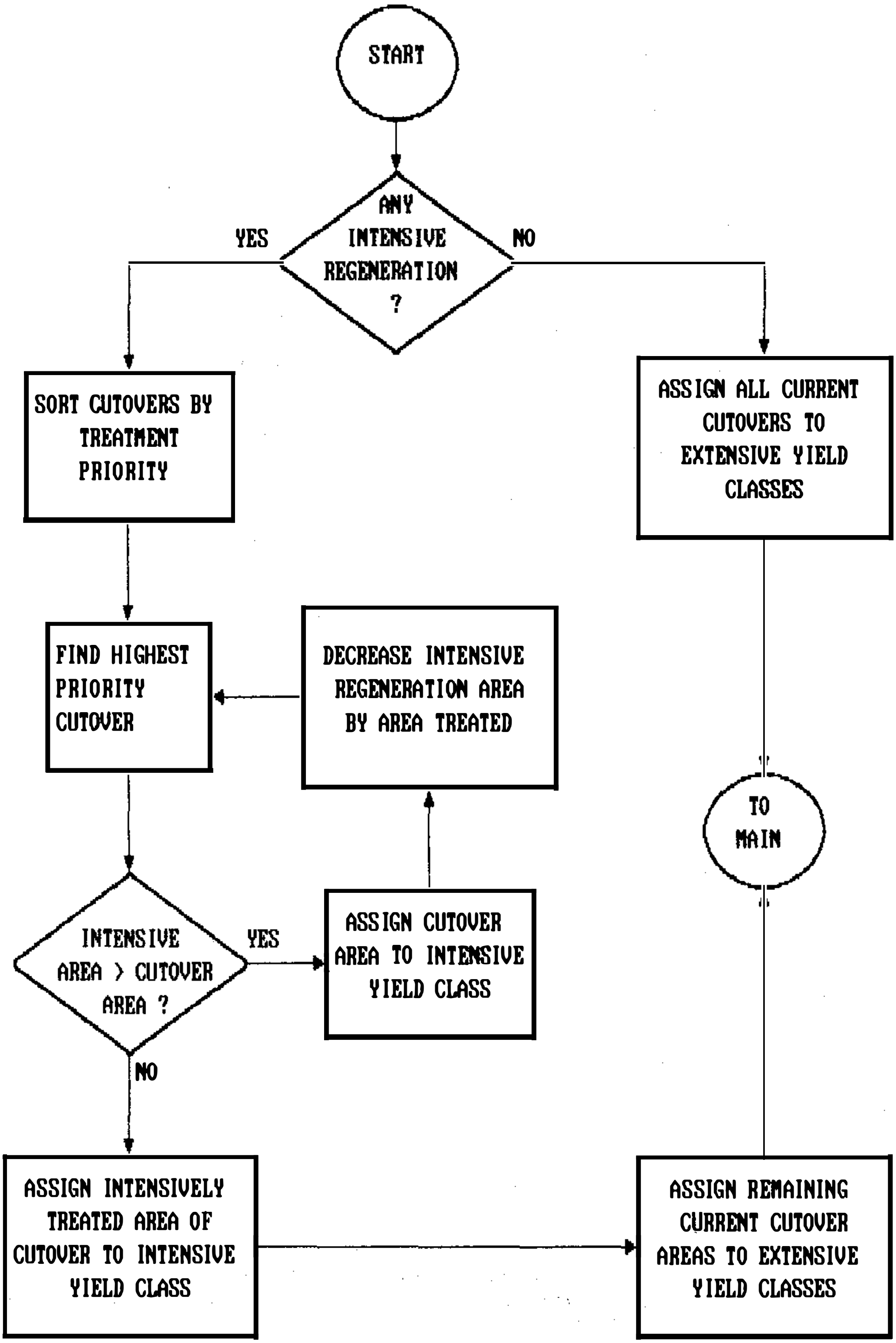

Figure 6. ATAMO regeneration routine.

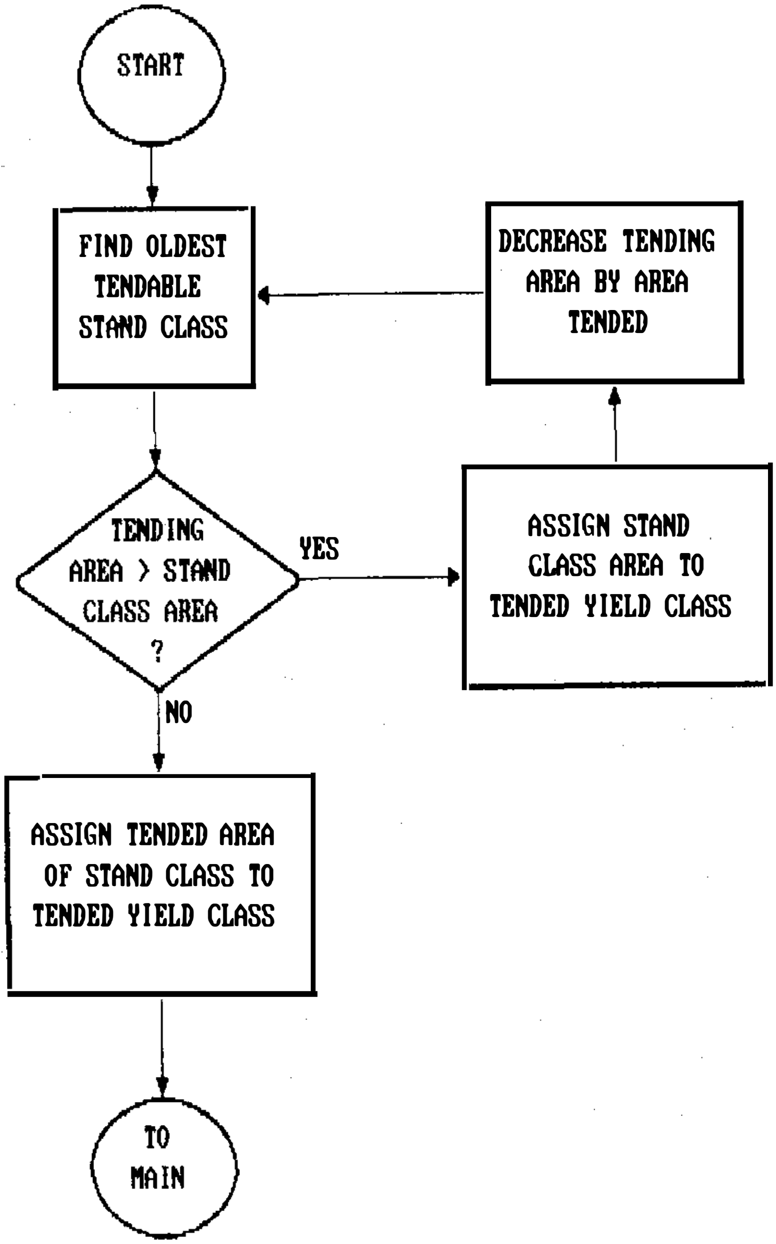

Figure 7. ATAMO tending routine.

(Fig. 8a). No consideration is given to yields from new stands established as the current forest is cut. When regenerated yields are considered, a higher sustainable harvest level may be found, because yields from new stands are available before the current forest is liquidated (Fig. 8b). This higher harvest level would deplete the current forest at a higher rate, resulting in a shorter rotation period and a reduced average stand-age at harvest. Figure 8c shows the additional ACE resulting from an intensive regeneration program. New stands are assumed to grow faster, and become operable sooner, than extensively regenerated stands. This allows a higher harvest rate on the current forest, which again leads to a shorter rotation period and a reduced average stand-age at harvest.

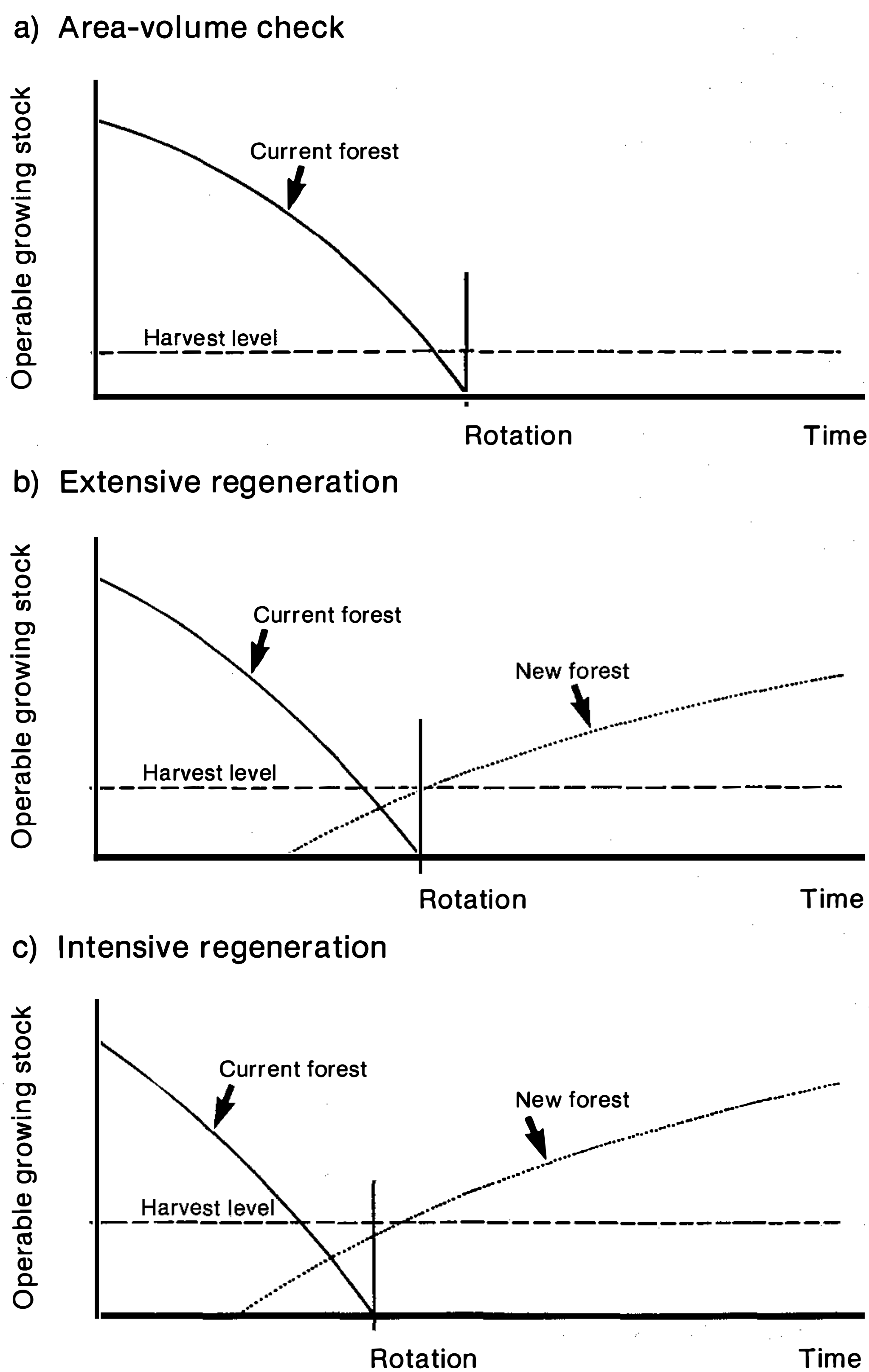

Figure 8. Allowable cut effects and rotations.

Risk

Catastrophic and endemic risks and uncertainties affect the forest (Dempster and Stevens 1987). Because ATAMO is deterministic and contains no direct allowance for risks, care must be taken in designing management strategies and in interpreting model results.

Risk is addressed by accelerating harvest of compartments at greatest risk. This should result in more compartments being harvested before being destroyed by fire or biotic agents. Compartments along transportation corridors, at lower elevations, and in other high-risk locations are considered for early operation. Because much of the forest is in a high-risk condition, this suggests that harvests should be accelerated in response to risk rather than reduced as previously believed by some (e.g., Alberta Energy and Natural Resources 1985). Long-term risk from catastrophic losses will be reduced by introducing more geographic diversity and by reducing the average ages within compartments. Replanning at least every 10 years will adapt the management strategy in response to catastrophes.

For the detailed FMP due in 1991, alternative approaches to risk management in wood supply analysis will be investigated. This will include studying the expected effects of long-term climate changes on risks.

CONCLUDING NOTE

The ATAMO model and the forest management planning system being implemented at Weldwood—Hinton represent incremental steps in the uniquely Canadian tradition of industrial forest management on public land as initiated here by Des Crossley with the first preliminary FMP in May 1956 (Crossley 1956). The preliminary FMP now being prepared is the fourth revision of Weldwood's FMP. At each revision over these past 33 years, changes to the planning process have occurred, but the basic management principles followed by Dr. Crossley, and used as models elsewhere, have been upheld. This is as it should be.

ACKNOWLEDGMENTS

Rick Bonar and Sean Curry provided useful comments on an earlier version of this paper. Bob Willing drafted figures 1, 2, and 8. Through his address presented at this conference, Tom Grabowski stimulated discussions between Hugh Lougheed and Sean Curry, which led to the ATAMO name. Tom described a critical point of a model's structure with the phrase "And Then A Miracle Occurs." This was repeated several times by later speakers in reference to the lack of transparency that often plagues models. We selected the name ATAMO to preserve this thought and to remind ourselves and others of the continuing importance of model transparency.

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QUESTION AND ANSWER SESSION

Question for Doug Walker by Jim Beck:

I'd like to ask a bit more on his regenerated stands, whether in fact he has taken account of anything like Hamish is talking about, whether there is any decline or whether his regenerated stands would be the same as his current stands or larger than his current stands, or whatever?

Doug Walker:

Yes. Actually, that is an interesting question, because the evidence we have at the company is a little unclear. One thing we have seen is that on pine cutovers that are doing well the yield from the regenerated stands appears to be about twice that of the old-growth stands at those ages. The reason I say it is unclear is that I'm not yet sure that those yields are typical. What I mean is that the stands we looked at (and where we obtained twice the yields) actually are drawn from the population of cutovers that is out there at random. I think there may have been some bias, and I don't know yet because I haven't looked closely, but I fear that there may be some bias in the way the stands were chosen for being included in that study. In general terms though, it appears that our productivity is increasing in the cutovers as compared to the old-growth forest. A very interesting thing that Bob Udell has observed is that the yields we are seeing now in our newest cutovers are higher than those in our oldest cutovers. What that means is that the average yields are increasing over time. So a cutover that is now 10 years old is performing at a higher rate on average than a cutover that we could have gone into that was also 10 years old had we gone into it 10 or 20 years ago. So there's this positive increase. Now we can't prove it yet, but we suspect it is due to climate change or who knows what else. The most plausible explanation I have is climate change. The drying hasn't caught up with us yet on that one, but the warming has.

Question for Hamish Kimmins:

This morning you suggested, I think, that we adopt a different approach to yield forecasting. I'm curious to hear what your priority impediments are to actually moving in that direction. What do you see as the major obstacles to proceeding as you suggested we should this morning?

Hamish Kimmins:

Well, first, it's more difficult. It's much easier to stick with a historical bioassay model, because foresters by and large are very well equipped and are very capable of measuring the kind of input premises that are necessary for that kind of model. When you start mixing some process simulation with the historical bioassay, inevitably it means some additional information over and above that which is necessary for the historical bioassay. That is the first impediment. Of course, dollars are going to be the bottom line. The only reason you would think of going that way is if you felt concerned that in fact things were going to change. If I was a professional forester, I wouldn't move away from a historical bioassay model unless I was fairly sure I needed to. If I was fairly sure I needed to, I presumably had pressure on me either from governments or within the company, of maintaining cuts, planning into the future, or I was under environmental pressure. The reason the Bureau of Land Management has gone away from the historical bioassay method and toward the FORCYTE method is because the public pressure for the public agency to demonstrate that they are indeed doing sustained yield is so great that they can't proceed with their planning until they have done this. So, I wouldn't go that way unless there was a good reason to do so. If there was a good reason, then presumably you can accept the cost of doing so.

Question for Hamish Kimmins:

Assuming that there are good reasons, are you suggesting that it is the cost of information acquisition that is the major impediment?

Hamish Kimmins:

Well, I think so, because there are a number of hybrid simulation models now available. There's the LINKAGE model, the FORET model, and the FORCYTE model. So you have a choice. They are different. They do different things. They're tending to converge. It's interesting; they are all tending to converge on a single common structure and common capability, suggesting that there is some common need, that there is something out there that would constitute an ideal model. Nobody has got there yet, but they seem to be converging on something that is similar.

If I were a forester who was facing very serious questions of weed competition that may significantly affect yields at the end of the rotation, if I was a forester who was considering, for a variety of reasons, age-class gaps in my inventory, going to shorter rotations, or if for a variety of economic or mechanization reasons I was going toward whole-tree harvesting, I would want to take a very good look at the costs of maintaining production in the face of those changes, what those costs were going to be, before indeed I went that way. So I see that there will be an increasing need. As Dr. [Gordon] Weetman said, whole-tree harvesting apparently has gone from 20% to 80% in the province of Quebec. Presumably, there will be foresters on some of the less-fertile soils in Quebec who will be starting to look at that question rather seriously.

Question for Doug Walker by Teja Singh:

Doug made a comment at the end on risk management, that when the forests are at risk it is better to cut down the rotation slightly to have a better chance of recovering or harvesting material that would be burned otherwise in a longer rotation. Yet the management tendency on the other side is to think that if there is a fire, what will happen, how will it meet their requirements for running the mill. How do you reconcile these two opposing views?

Doug Walker:

I don't actually right now. In fact, the response that we're taking now is that we're trying to identify those compartments that we perceive to be at highest risk: those along road corridors, at lower elevations, or where there's a lot of human traffic. We're in effect upping the priority for those compartments to be operated. What we're hoping to do there is to change the age-class distribution and, in essence, the fuel complex in the highest risk areas. At the same time, the other statements I was making are as much arguments against having an allowance for fire as they are for an increase in the harvest rate. We are not going to be proposing an increase in harvest rate, but what we are going to be proposing is that there should not be any decrease in harvest rate because of risk.

Question for Hamish Kimmins:

Some of the logging method terminology that you're using is getting me confused. When you're talking whole tree are you really meaning full tree, and when you talk complete tree are you meaning whole tree? Because full tree is above stump, whole tree is with stump, and complete tree is with roots.

Hamish Kimmins:

I was using the terminology used by Professor Young at the Whole-Tree Harvesting Institute at Orono, Maine, which is perhaps getting a bit dated now. Yes, it's very confusing. A whole tree was everything above stump, and complete tree included roots. I apologize for the confusion. I agree that it is a bit dated, that terminology.

Question for Doug Walker by Imre Bella:

I'd like to ask Doug if he could comment or give a little more detail as to what you actually use to predict the outcome of different intensive management activities like thinning or planting.

Doug Walker:

I can't answer it yet, Imre, because we're in the process of doing it, and honestly I don't know. We have looked, a little, but in a different way, at using what we think might be expected impacts on MAI, just as a very crude approximation from stand tending tactics after having identified how much of the forest management area it really is appropriate for us to even look at. It looks to us like the impact is not very large. That's as good an answer as I have in terms of tending. In terms of intensive regeneration, we are again in the process right now of trying to identify for the various cover types what might be reasonable intensive regeneration options and what we might expect as yields from those. We can use the example of our pine sites. Perhaps we can expect there that we can enjoy twice the precut productivity, but we can't quantify it yet much more than that. A component of our PSPs has to do with regenerated stands, but our distribution of types within those stands is pretty broad. We don't really have for most of the cover types all that much quantitative data that we could use to develop a good estimate of the yield increases or increments that would come about from intensive regeneration. We're working on it, and we're aware of it. I think, as you're aware, our whole forest inventory and growth and yield programs are under review now, outside review, and I expect that there will be some dramatic changes in the way we go about collecting inventory data, including growth and yield data.

SESSION III:

NEW DIRECTIONS IN MODELING

NEW DIRECTIONS IN NATIONAL TIMBER SUPPLY MODELING

K.L. Runyon
Forestry Canada
Fredericton, New Brunswick

This presentation showed background, approach, current status of work, and plans to assess Canada's timber supply by Forestry Canada. This study was started early in 1987 as a result of continuing uncertainty over Canada's timber supply. The approach has two phases. The objective of Phase 1 is to identify and report on the physical and economically available timber now and over the medium-term by province and principal product and species groups. This is essentially a descriptive reporting of the current status and outlook for timber availability as determined by each province.

The second phase is a more analytical approach that looks at demand and economic factors more explicitly. This phase has two main objectives. These are as follows:

1. to model timber market activity (supply and demand) to provide estimates of production, consumption, and prices of roundwood for principal geographic regions in Canada and for product groups; and

2. to provide projections by computer simulation of timber market activity and corresponding impacts of a variety of forest management, industrial development, and trade policies.

Preliminary results of Phase 1 and progress and plans for Phase 2 were discussed in the presentation.

A FRAMEWORK FOR ANALYZING SILVICULTURE PROGRAMS

C.V. Pearce, T. McDaniels, and C. Swoveland
Consultants
Vancouver, B.C.

INTRODUCTION

Silviculturists and forest planners are responsible for identifying which areas of a forest should receive silviculture treatments and the appropriate treatment options for each site. Because funds are limited, it is important to allocate monies to projects that will provide the maximum expected returns. Yet, because of the variety of forest conditions and range of possible treatments, relatively little is known about the likely effects of specific silviculture practices in a given location. For example, is fertilizing a given stand of pine likely to produce more benefits than thinning a different stand of spruce?

More specifically, the questions that must be answered in order to make informed decisions are these:

What are the objectives that silviculture expenditures hope to achieve?

What are the criteria that should serve as the basis for evaluating options relative to these objectives?

How should uncertainties regarding the effects of various silvicultural treatments be addressed?

How should uncertainty over the values of alternative timber outputs, future conversion capacity, and rotation ages be considered?

How should allocation decisions be made in order to maximize the productivity of these investments?

Silviculture investment questions are a classic example of decision-making under uncertainty. Decisions must be made in the near term regarding the choices between investment options. These decisions will ultimately affect the size, quality, and timing of forest harvests that will occur decades into the future. The long lives of trees and the range of environmental conditions occurring in the forest necessarily mean that the efficacy of various silviculture practices are not well understood in many situations. Other uncertainties are introduced by exogenous factors such as weather during crucial growth periods, possibility of insect infestations, possibility of fire, and the future values of alternative products. All of these factors interact to make a complex, long-term decision problem with multiple sources of uncertainty.

This problem has historically been analyzed using models that focus on stand-level decisions or, at the opposite end of the scale, using yield analysis models. The existing stand-level systems allow the user to evaluate many options, and in some cases, probabilities of treatment success are included in the analysis (Payandeh and Field 1985). Forest level effects of treatment options cannot be evaluated with stand level models. In the yield analyses systems that are designed to evaluate forest-level effects, computational limitations severely constrain both the numbers of forest types and the treatment options that can be analyzed. Uncertainties also cannot be incorporated (Sedjo 1986).

The current practice in Canadian silvicultural planning largely ignores these uncertainties. If silviculture investment options are compared and analyzed at all, the usual approach is to proceed in a deterministic framework, as if all factors were known with certainty, and to pick the best option on that basis. More often, silvicultural options are selected on the basis of rules of thumb or qualitative assessments by managers that reflect their views on the effectiveness of various treatments, and the types of raw materials the forest industry conversion facilities will demand in the future. Although such subjective judgments are an important input to any decision process involving uncertainty, they must be made explicitly and consistently if they are to provide a defensible basis for allocating funds.

The importance of the pending timber crisis, the magnitude of the planned expenditures, and the complex uncertainties associated with the effects of silviculture treatments all point to the need for an improved evaluation tool to aid managerial decision-making.

SYSTEM OBJECTIVES

This paper describes work undertaken for Forestry Canada to develop an analytical framework to help gain insights into these complex decision problems. The objective of the project is to develop a prototype of an evaluation framework that explicitly accounts for uncertainties and evaluates the expected results of silviculture practices. The management objectives include economic benefits, contributions to short- and long-term timber supply, and regional impacts in relation to short- and long-term employment generation.

The system is designed for use by silviculturists evaluating treatment options for individual stands and forest planners who are more concerned about forest-level objectives. The natural decision processes of these users define the structure of the evaluation system. Local silvicultural knowledge is incorporated in the analysis through opportunities for the users to select appropriate treatment options and to estimate the uncertainties affecting the success of combinations of these treatments. This has led to the development of a flexible analysis system.

It is important to stress that this is a decision support system designed to provide insight into these decisions. The system is not intended to replace the role and responsibilities of established decision makers. The objective is to structure the decision process and to test the outcomes of interrelated factors.

ANALYTICAL FRAMEWORK

Decision analysis draws on operations research, statistics, economics, and psychology. It has evolved over the last 20 years to deal with problems that involve a complex structure with uncertainties and multiple objectives (Raiffa 1968; Bodily 1985). Decision analysis has been characterized as "formalized common sense for problems where informal common sense is not up to the task."

A series of silvicultural treatments leads to a forest stand composed of certain species with growth patterns depending on the productivity of the site and the uncertainties associated with the treatment options. A decision analysis can help determine whether the benefits derived from the stand conditions created by the treatments warrant the costs.

Measuring Treatment Benefits

In a management context, the objectives of a program represent the conditions that are important to the decision makers. The benefits that are measured in an analysis should represent these objectives. Many different benefits could be included in the evaluation of a silviculture program. The challenge is to select the measures that most closely represent the objectives of the program.

In this system the user selects the combination of economics, wood supply, and employment benefits that represent the program objectives. These benefits can be measured at the stand level or from the perspective of the whole forest. At the stand level, timber supply benefits are measured by the increase in merchantable volume attributed to the treatment. Economic benefits accrue from an increase in the value of the products, net of silviculture and processing costs. Employment generation is based on changes in employment due to the treatments and the utilization of the wood fiber.

Silviculture treatment decisions are seldom based on a single stand. These decisions are part of a management strategy for an entire forest. Benefits from the perspective of forest level analyses are based on the changes in wood supply patterns that result from the altered growth of the stand after the prescribed treatments. Long-term changes in forest yield represent the wood supply benefits; the economic implications of these changes represent economic benefits, and employment benefits are represented by the differences in employment due to the change in yield.

Long-term harvest levels for the growth projections associated with the treatments must be evaluated to calculate forest-level benefits. This analysis is done using a linear program. The expected harvest flow is calculated for the range of yield curves that are expected from the combinations of treatments on the forest types. A post-optimality analysis is performed in which the marginal benefit of changing the growth of a hectare of the forest from one yield curve to another is calculated and recorded in a benefit matrix that is stored for future use. These values are used to calculate the marginal forest level benefits of the prescribed treatments. Separate matrixes are constructed for economic, wood supply, and employment benefits.

Selecting the Best Treatment for a Site

A decision-tree analysis is used to identify the best treatment combination for each forest type. Figure 1 illustrates the structure of a simple decision tree representing the treatment options for a particular forest type. The large number of treatment options and the multiple uncertainties arising from these combinations are best analyzed using the decision-tree approach. The appropriate treatment options and the probabilities of success for each treatment are defined by the user.

Each combination of treatments yields a range of final stand conditions, depending on the expected success of each treatment. This information is used to calculate the benefits of a particular combination of treatments. Again, these benefits can be measured from the perspective of the stand alone or on the influence across the forest. Figure 2 shows the relationship between the linear program yield analysis and the decision-tree analysis. In this analysis, the best treatment combination is the one that maximizes the net value of the selected benefits.

Selecting Sites to Treat Within the Forest

Budget constraints often limit the treatments that can be carried out within a forest area. The relative benefits of expending one dollar to carry out a particular treatment on Site 1 versus a different treatment on Site 2 should be assessed. An evaluation of the proverbial "bang for the buck" is needed.

This is done by ranking the best treatments for each site according to the ratio of net present value divided by the silviculture treatment costs. This ratio represents the net value derived from each dollar of budget that is invested. The highest ranking projects based on this criteria would be implemented within a forest until the budget is exhausted. The economic, wood supply, and employment benefits of various budget levels can also be assessed using the output from this system.

INFORMATION REQUIREMENTS

The following data are required to carry out an analysis:

- forest inventory;
- treatment combinations and probabilities of treatment success for each forest type;
- yield curves;
- treatment costs;
- economic values (processing costs, product values, etc.)
- employment created;
- weighting of objectives; and
- yield analysis constraints.

Figure 3 describes the relationships among these data bases in the analysis. The data tables have been structured to conform with existing data bases as much as possible. An important source of information will be expert judgments. One of the key aspects of the project will be to obtain probabilities or other quantitative measures describing the uncertainties associated with silviculture treatments. The prototype will be calibrated for a coastal Douglas-fir example. Future projects will provide default data for other applications.

SOFTWARE CHARACTERISTICS

The prototype has been developed for use on an IBM-compatible microcomputer for individuals with a minimum of computer experience. Users are prompted to input data through a series of nested menus. An example of this process is illustrated in Figure 4. Most of the data tables can be altered by the user. The nested menus provide the user quick access to the data bases for editing. The screens and menus can be quickly reprogrammed to improve the user interface.

The yield analysis using a linear program may take several hours to execute. This has been a limitation to microcomputer application of linear programming for yield analyses. In this system, however, once the marginal benefit matrix is calculated for one formulation of the yield analysis, this matrix is stored and used for a number of decision-tree analyses. This feature provides the user access to a powerful linear program to calculate the optimum harvest flow without the disadvantage of having to resolve the harvest scheduling problem whenever changes are made in the silviculture treatment options or the probabilities of treatment outcomes.

SUMMARY

A comprehensive system is needed to assess the relative benefits of alternative silviculture expenditures within a forest management area. A decision-

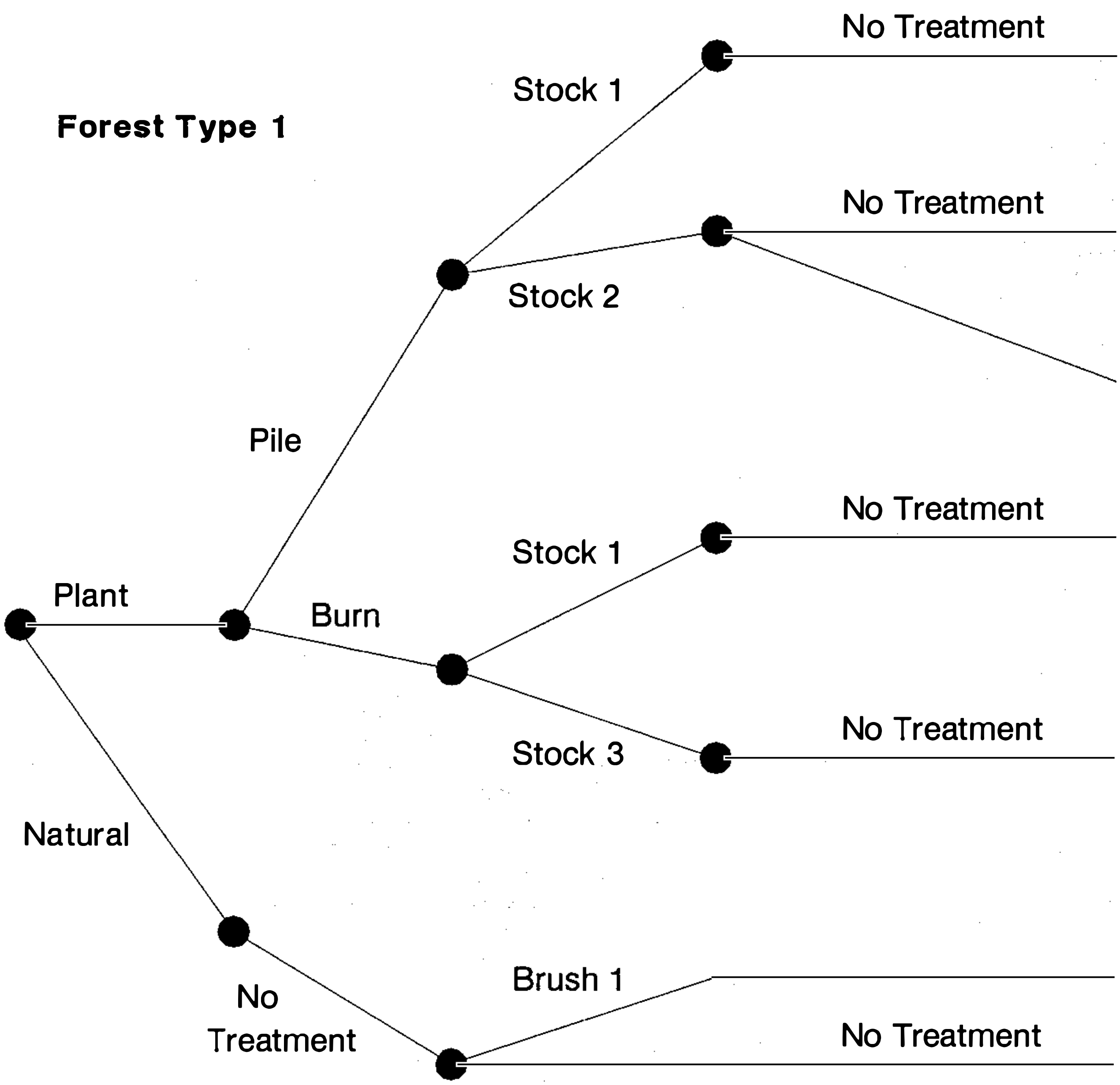

Figure 1. Decision-tree representation of silviculture treatment options. Note: the probabilistic outcomes are not displayed at each node for simplicity.

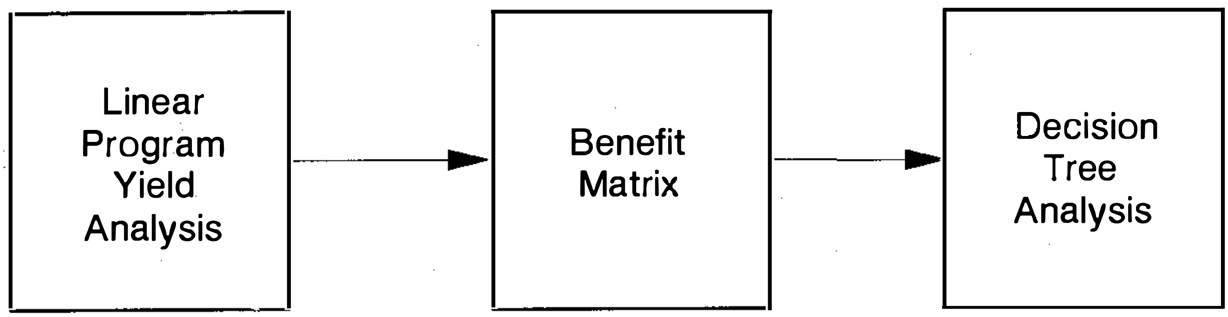

Figure 2. Relationship between the linear program and the decision-tree analysis.

tree analysis is used in this prototype to evaluate feasible treatment combinations and their interrelated probabilities of success on a specific site. This analysis is linked to a linear program that identifies the optimum long-term harvest levels within the forest-based defined constraints. This yield analysis defines the forest level benefits of alternative growth projections. The treatment options within the forest are ranked based on a benefit-cost ratio using the combination of economic, woodsupply, and employment benefits defined by the user.

This decision support system will help silviculturists and forest planners understand the complexities associated with silviculture treatment decisions. It also provides a tool to investigate the outcomes due to the perceived success of various treatment options.

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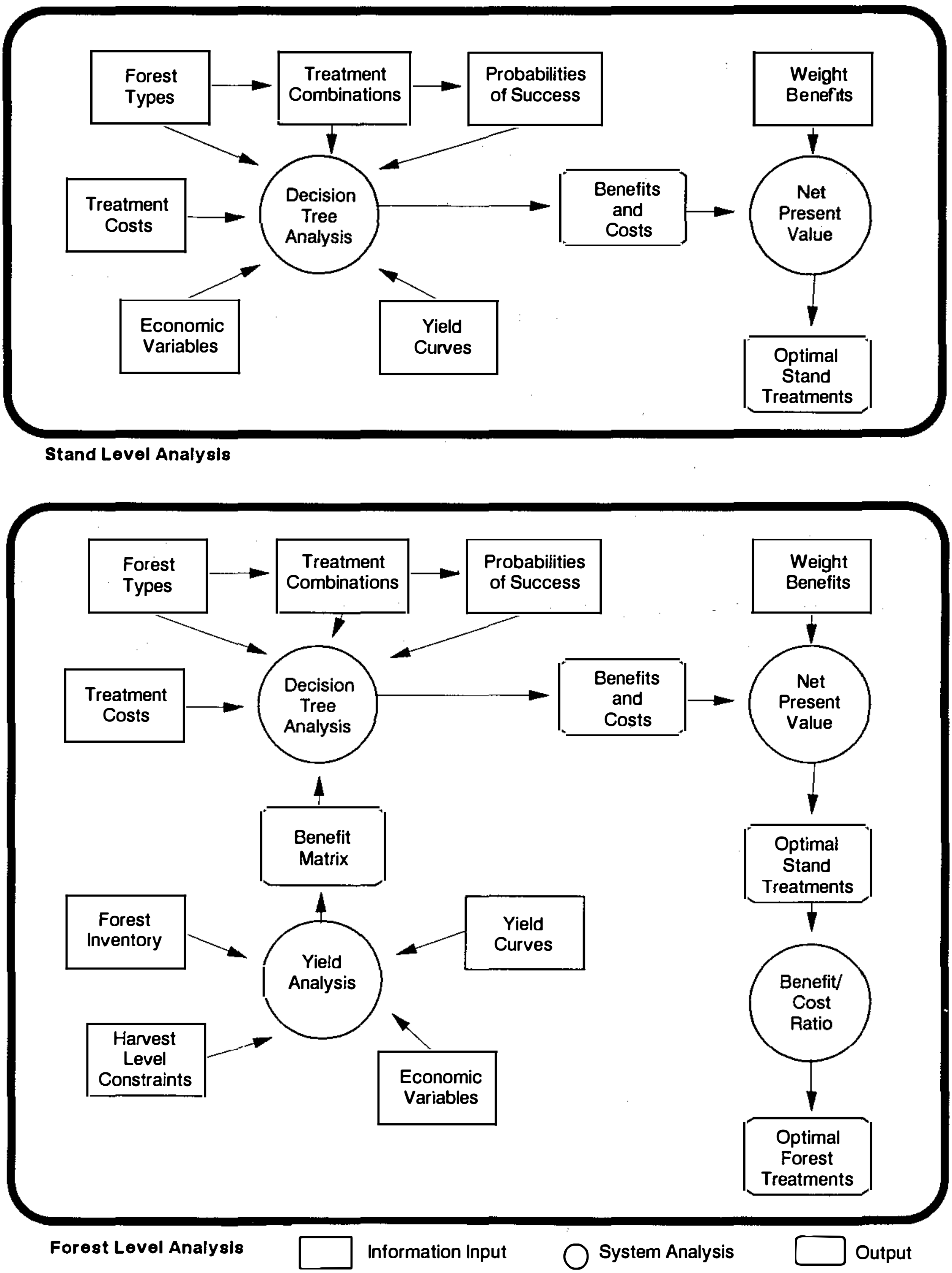
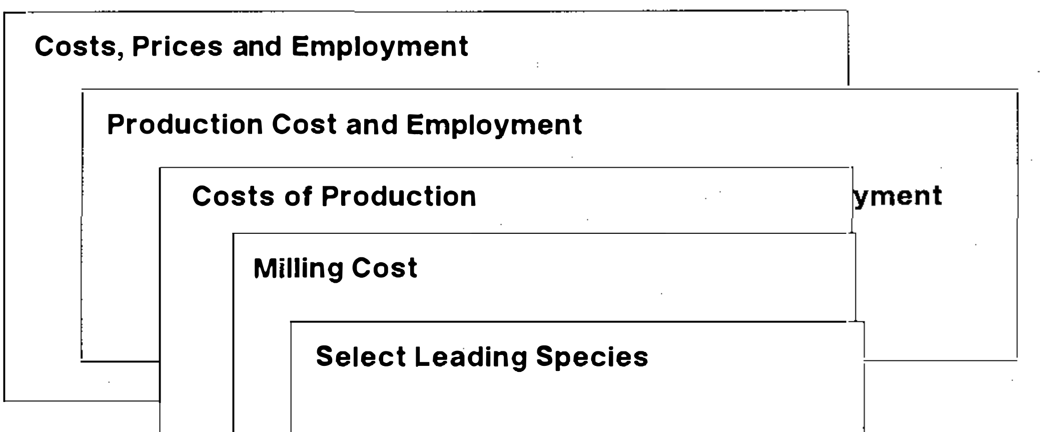


Figure 3. Relationship of data bases in the stand and forest level analyses.



Milling Cost
($/unit of product)

Leading Species: Ba

Wood Product			Base Year	Year 2000	Years 2020+
Studs	High	Mfbm	0	0	0
Studs	Medium	Mfbm	0	0	0
Studs	Low	Mfbm	0	0	0
Dimension	High	Mfbm	0	0	0
Dimension	Medium	Mfbm	0	0	0
Dimension	Low	Mfbm	0	0	0
Chips		BDU	0	0	0

Figure 4. Example of nested menus and input screens.

PRACTICAL APPLICATIONS IN FOREST MANAGEMENT PLANNING

D.J. Depta and M.A. Brathovde
Weyerhaeuser Company
Tacoma, Washington

ABSTRACT

The integrated set of forest planning systems developed at Weyerhaeuser Company has allowed us to assess and respond to the changing biological and economic conditions that influence the company's intensive forest management program. In more than 20 years of use and evolution, these systems have demonstrated sufficient breadth, depth, accuracy, and ease of use to accommodate an array of practical forest planning questions. Two illustrative applications are described—one involving individual cutting-unit log forecasting and another involving international wood-flow projections.

BACKGROUND

The High Yield Forestry (HYF) program was formally initiated at Weyerhaeuser Company in 1966 with the conviction that intensive forest management represented an attractive financial investment opportunity. Not only could intensive management increase our long-term returns, but through such factors as the allowable cut effect (Lundgren 1987), the net worth of our existing unmanaged natural timber could also be improved. We were further convinced that research efforts into tree genetics and biological growth processes would serve to further enhance the attractiveness of the HYF program. After more than 20 years, we remain committed to these beliefs.

From the HYF program's inception, we understood that there were numerous forces, biological and economic, that would interact to affect the program's success or failure. To operate effectively in this complex environment we recognized the need to develop a forest management modeling system to assist us in 1) formulating appropriate management practices, 2) monitoring our progress against those practices, and 3) refining and redirecting the program in response to the changing world in which we operate. Out of this belief we developed the Timberlands Strategic Planning Systems Network (Fig. 1). This systems network has been described elsewhere (Depta 1984; Wakeley 1987) and will only be summarized here for background information.

WEYERHAEUSER FOREST MANAGEMENT SYSTEMS

As illustrated in Figure 1, developing a management plan for our properties makes use of several systems, each driven off of a common inventory base. The arrows connecting the four planning systems show that each may be run independently or in conjunction with the others. One system may even be run as a subsystem of another. This ability to operate independently or as a network substantially increases the flexibility of the systems and allows applications to be tailored to specific needs.

A brief overview of the key functions performed by each individual system is presented below.

The Forest Inventory System provides an up-to-date stand by stand data base of all company land and timber for common usage in the planning systems. It also assures consistent and accurate monitoring of inventory changes through time. It is a multiple-overlay geographic information system (GIS) using stand table modeling and tree taper equations for the timber inventory segment.

The Silviculture Prescription System projects the growth and yield of individual timber stands or other broader inventory units based on a specified set of silvicultural treatments. By altering these treatments and assessing the results in both financial and risk terms, a prescribed management plan can be developed for the unit.

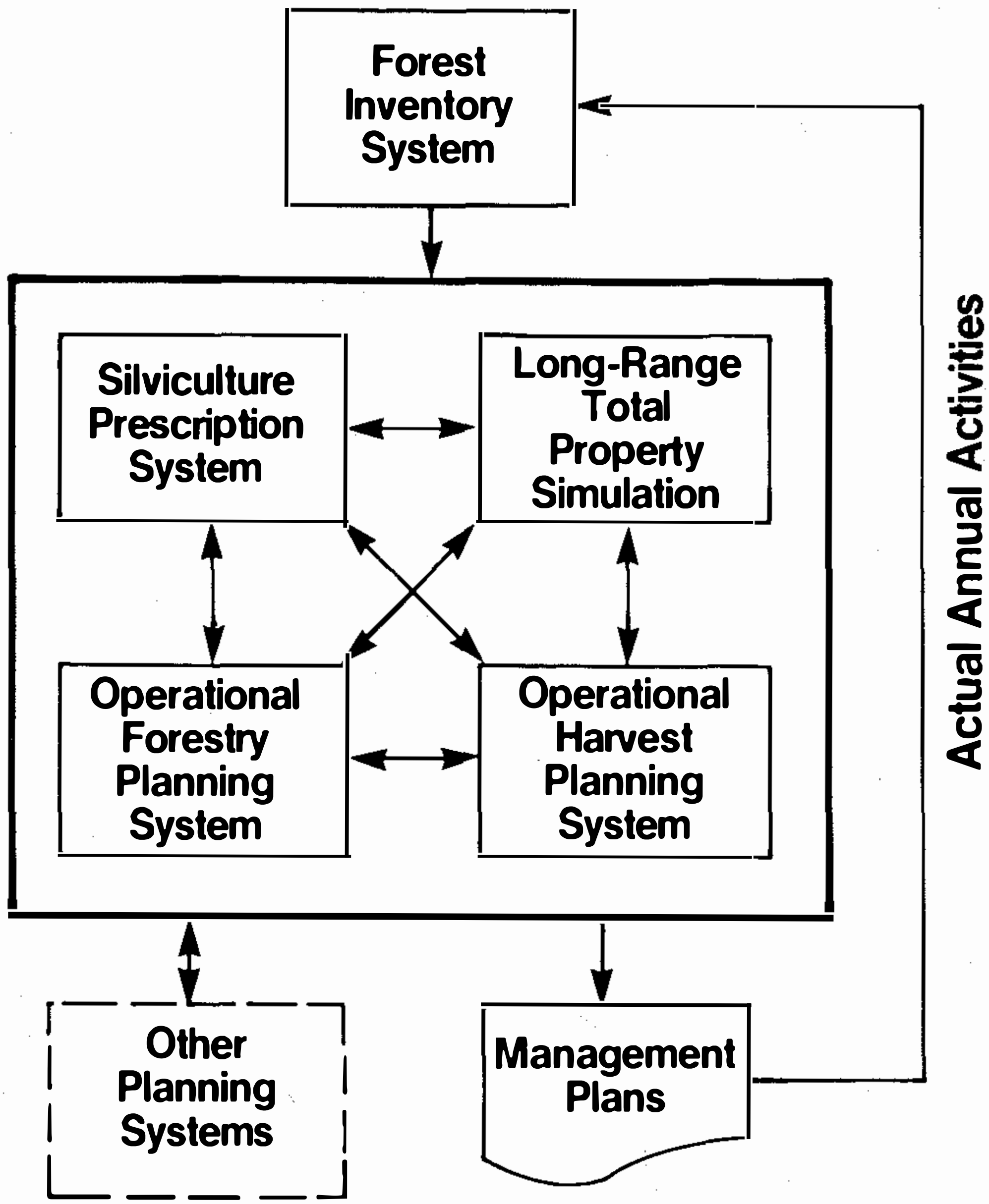


Figure 1. Timberlands Strategic Planning Systems Network.

The Long-Range Total Property Simulation brings together the stand-based inventory and the attendant silvicultural prescriptions to produce a total property plan. This plan normally covers a 50-100 year period for an entire operating region and includes annual harvest levels, log and product mix forecasts, silvicultural treatment levels, and pro-forma income forecasts. It is particularly useful for computing near- and long-term harvest levels that are consistent with the standing merchantable inventory and the development of the intensively managed plantations.

The Operational Harvest Planning System supports the selection and sequencing of individual cutting units over the next 1-15 years. It receives data from the inventory system for the stands nearing harvest age, then assists in building a detailed harvest plan consistent with the harvest levels developed in the Total Property Simulation. In the process, consideration is given to specific facility needs and other operational constraints such as access limitations, regulatory restrictions, etc. Forecasts of cutting unit volume, log size, log quality, species mix, and financial growth rates are key outputs.

The Operational Forestry Planning System is used to plan forestry treatment budgeting and workload over the next 1-15 years and for forecasting thinning removals. The existing system utilizes the inventory as the data base and maintains a ledger of individual plantations by silvicultural prescription. Basic data and biometric algorithms are shared with the above systems.

Other planning and reporting systems also use the output of the inventory and forestry planning systems. These include applications such as facilities log allocation and mill models, total company midterm income projection, and annual timber lands performance reporting.

SYSTEM APPLICATIONS

This paper will focus on the use of this systems network and its relevance to business-oriented strategic planning. Some of its generic uses are listed in Figure 2. The diversity of applications shown is indicative of the system's utility and versatility over the past 20 years.

There are too many individual applications to discuss in detail. We have instead chosen two examples (indicated with arrows in Figure 2) that illustrate the depth and breadth to which the systems network can be used:

- *Cutting-unit log forecasting* is chosen to illustrate the depth of detail at which the system is capable of operating.
- *International timber supply projections*, using New Zealand as an example, is chosen to illustrate the breadth to which the system can be applied.

HARVEST FORECASTING AT THE CUTTING-UNIT LEVEL

Harvest forecasting at the individual cutting-unit level is normally performed in the Operational Harvest Planning System. It tends to be one of the most detailed uses of the Timberlands Planning systems network, and it serves to illustrate the depth to which the system can function. In this use, an accurate representation of the detailed log mix anticipated from a specific harvesting unit is desired. Such a forecast is illustrated in Figure 3.

Here it can be seen that the basic level of inventory data is the timber component within an individual timber stand. In all, our property is divided into 115 000 timber stands. Each stand may have up to nine individual timber components to describe its multistory and multispecies characteristics. In this case the timber stand consists of three components —two of Douglas-fir (*Pseudotsuga menziesii*) (Mirb.) Franco) and one of alder (*Alnus rubra* Bong.). Simulating its harvest today (left side of chart) involves fitting stand tables to the individual component descriptions, then applying tree taper equations to estimate the log mix by small end diameter inside bark (dib). Log value tables provide estimates of the resulting harvest value.

If we want to estimate the log mix and value at a later point in time, the inventory description is updated by a series of growth algorithms, and the stand table, log mix, and log valuation are recomputed. The results shown on the right side of Figure 3 include 10 years of growth. This capability not only allows us to forecast future log mix for downstream facility planning purposes, but the revaluation further allows computation of the financial growth rate for the harvest unit over time.

The timber stand illustrated in Figure 3 shows a stumpage value growth rate of 3.3% (real) com-

- ➡ Cutting unit log forecasting and value growth estimation
- Fee estate long-term harvest level and log mix projections
- ➡ International timber supply projections
- Comparative wood growing costs, regionally and worldwide
- No-fee purchased wood availability projections
- Annual income statement forecasting
- Discounted cash flow analysis of alternative management strategies
- Seedling and nursery facility requirements through time
- Forestry workload forecasts
- Forest fertilizer supply requirements
- Log flow and facilities allocation
- New facilities planning
- Legal accounting requirements (tax and Securities and Exchange Commission reporting)
- Annual timberlands performance reporting
- Valuation of proposed technology improvements
- Individual stand silvicultural prescription development (natural and planted stands)
- Capital allocation – Timberlands versus other divisions, between geographic regions within Timberlands, alternative silvicultural treatments within region
- Timberlands acquisition and disposal analysis recognizing parcel synergies with the total estate
- Silvicultural program and treatment tracking – permanent inventory records of fertilization, etc.
- Seasonal constraints on wood flows
- Product mix forecasts (e.g., lumber mix)
- And more

Figure 2. Historical systems applications.

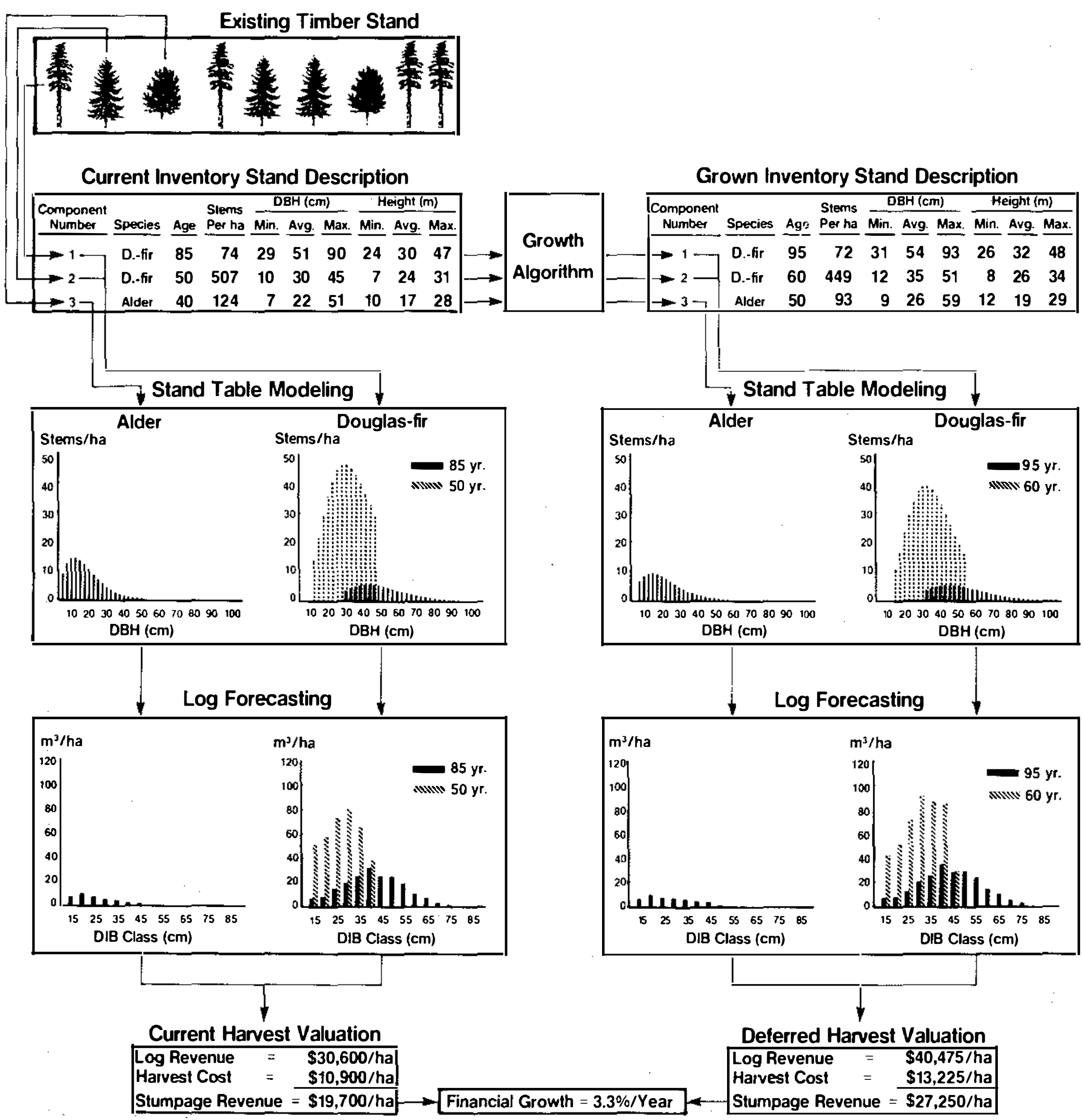


Figure 3. Cutting-unit log forecast and financial growth.

pounded over the next 10 years. This is a low financial growth rate, and we would consider the stand overmature and ready for harvest. In planning and sequencing the harvest we would want to cut this stand after any stands showing still lower financial returns but before those demonstrating higher returns. In actual practice, operational harvest planning becomes more complex when the seasonality constraints, specific facility needs, roading plans, and outside purchase opportunities are considered.

INTERNATIONAL SUPPLY PROJECTIONS

At the other end of the spectrum, our international wood-flow projections illustrate the breadth to which the systems can be applied. In these projections the level of geographic detail portrayed in the previous example is not necessary, nor is the detailed inventory information available. Our objective in these international wood-flow forecasts is to understand the likely level and character of global timber supplies through time. Such an understanding helps us to position and manage our own wood flows toward those raw material types expected to be in short supply. Conversely, we can avoid growing raw material types likely to be in oversupply. Although international wood supply forecasts are available elsewhere, we have chosen to produce our own simulations to provide 1) the desired level of detail regarding the character of the timber supply (e.g., log mix), 2) the ability to sensitivity-test different future scenarios, and 3) consistency of methodology and results across geographies.

In using the forest management planning systems to investigate these issues, we employ an option in the Total Property Simulation whereby aggregated inventory information is input to the system instead of detailed, stand-level information. This option permits the system to quickly and inexpensively produce log forecasts for large international geographies under a series of future scenarios.

The case of New Zealand was selected to illustrate these international simulations because it is simple to explain, most of the basic data is publicly available, and the results can be compared to similar estimates by others (Sutton 1986). It also illustrates some of the more dramatic wood-flow changes expected to occur internationally. The results of our base case projections are shown in Figure 4.

Only two basic items are required to generate the Figure 4 results: 1) a statement of inventory and 2) a set of yield tables with attendant management assumptions. Examples of these are shown in Figure 5.

In the case of New Zealand, the inventory by age class is publicly available (Butler et al. 1985). The yield tables, however, were constructed from a combination of published information and personal judgment. In New Zealand, as elsewhere, the forest comprises a variety of species and management regimes. To illustrate the computations, however, only one of the yield tables actually used is shown (Fig. 5). This yield table is intended to reflect what is commonly known as "old crop radiata" in New Zealand. It applies to radiata pine (*Pinus radiata* D. Don) planted at high densities and otherwise left untended. This type of management is evident in the bulk of the timber being harvested in New Zealand today, whereas other practices (e.g., intensively managed, pruned plantations) become more important in the future harvest.

To illustrate, the yield table consists of volume and log mix information by age (Fig. 5). The log mix has been determined by estimating the stand table parameters (average, minimum and maximum diameters, and heights as shown in the previous log forecasting example) for each age class within the yield table. These parameters are then used to generate a stand table. Next, using tree taper equations, the log mix is estimated for each age class. Of course, tree taper equations are not available for most of the world's species. In these cases, we use judgment and other available information to select one of our existing taper equations.

The Total Property Simulation System then uses these two general data sets to produce the resultant forecast shown in Figure 4. The upper left panel in Figure 4 is simply a display of New Zealand's current inventory by age class as reported in Figure 5. Numerical processing begins by harvesting the oldest stands first (other harvesting priority schemes can also be modeled). Based on the age of the stands being cut (in this case 70 years old; see top center panel of Figure 4), the volume and log size mix are simply interpolated from the yield table. Additional inventory age classes are cut and their volume and log mix accumulated until the harvest level for the first year of the forecast is achieved (upper right panel). The log mix comprising the first year's harvest and any scheduled commercial thinnings, is then reported (lower left panel).

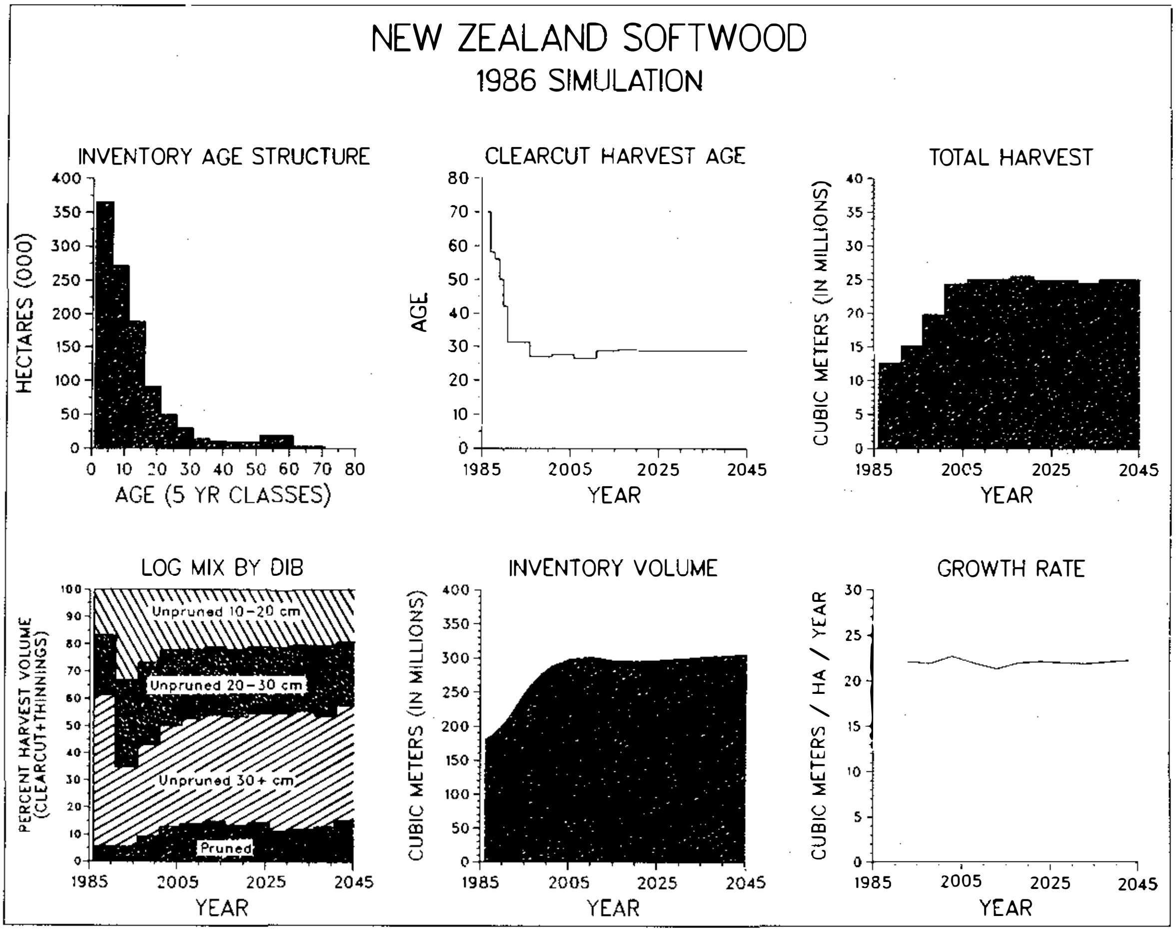


Figure 4. New Zealand softwood simulation.

Softwood Inventory

Age Class	Area ha(000)
1-5	365
6-10	271
11-15	187
16-20	91
21-25	49
26-30	30
31-35	13
36-40	10
41-50	18
51-60	39
61-70	6

"Old Crop" Radiata Yield Table

Age	Yield (m^3/ha)	Log Mix % By DIB (cm.) 10-20	20-30	30-40	40-50	50+
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
55	760	6	10	21	31	32
60	770	6	8	18	27	41
65	779	5	7	15	24	49
70	787	4	5	13	21	57
75	794	4	5	9	15	67
80	800	4	4	9	15	68
-	-	-	-	-	-	-
-	-	-	-	-	-	-

Figure 5. Input data for New Zealand simulation.

To project the next year, the remaining uncut inventory is advanced one year in age, and "age zero" hectares are updated for estimated reforestation and afforestation. A new inventory volume is then derived (bottom center panel) by accessing the yield tables with the new age-class distribution. Shifting the inventory forward in the yield tables by one year also provides an estimate of growth (bottom right panel). The harvesting and log mix process described above is then used again to forecast the second year's wood flow, and the process repeats itself until the complete simulation is developed. Results may then be reported by year or accumulated and reported by time period, as was done in Figure 4.

Once the base case simulation is completed, we commonly subject it to scenario testing such as different afforestation rates, changes in stand management assumptions, or different harvest levels. In the above example, we have allowed the system to internally compute annual harvest levels that will affect a smooth transition from today's inventory structure to a fully regulated state. Other harvest algorithms, including prespecifying the future harvest to match external studies, are also options. For example, in the case of New Zealand we have run a simulation using the government's harvest forecast (New Zealand Ministry of Forestry 1988). In addition, because the computer output files for all simulated geographies are in the same format, we can accumulate the resultant log mixes through time and across international geographies and then compare them to our own future harvest.

As illustrated, the process can be quite straightforward. Of course, geographies of special interest to us receive a more intensive effort, while those of less interest receive less attention. Basic data is generally more difficult to obtain than in the case of New Zealand. Nonetheless, the ability to accommodate simple and understandable approaches is what has enabled us to simulate international wood flows by specific geographical area, species, and log size. Because the inputs and algorithms are simple and yet biologically relevant, it is easy to discuss the results and modify the inputs as necessary. We have reviewed our international forecasts with more than 50 foreign visitors over the past 3 years and have found their input to be most helpful in upgrading the quality of our data base for their particular areas.

The New Zealand illustration describes an extensive application of the Total Property Simulation System. As mentioned earlier, much more intensive projections are made for our fee ownership and prospective acquisitions. A further application of this Total Property Simulation System in the context of a Canadian tree farm license can be found in a paper by Steve Tolnai of Weyerhaeuser Canada (Tolnai 1987).

CONCLUSION

In conclusion, the motivation for the Weyerhaeuser HYF program remains to improve the financial performance of our major investment of large timber holdings. Improvement occurs through managing the interaction between the biological and economic factors that affect not only our managed plantations but also our natural second growth and old growth timber. The success of the HYF program has been significantly assisted by the development of a network of forest management systems that are biologically appropriate and relevant to business decisions, yet understandable and versatile enough to support the numerous applications that are required to implement and enhance a major program like the Weyerhaeuser High Yield Forest. The evolution and enhancement of these systems continues.

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INTEGRATED FOREST OPERATION PLANNING

E.W. Robak
University of New Brunswick
Fredericton, New Brunswick

INTRODUCTION

Errors made in the formulation of an annual operating plan can result in reduced profits and increased risk for forest product companies. Operational planning is a complex process, and the detailed analysis that can lead to higher profits and lower costs and risks can be very time-consuming. Studies of forest operational planning practices in Canada (Robak 1984) suggest that insufficient analysis is undertaken to ensure that planned operations are reasonably efficient and effective. Forest operation planners themselves expressed the opinion that they were not being given the time or tools to formulate good plans.

This is a phenomenon I observed as a forest operation manager in eastern Canada in the late 1970s and which I later confirmed by conducting the above-mentioned study as a faculty member of the department of forest engineering at the University of New Brunswick in the early 1980s. I knew by experience that better planning could result in hundreds of thousands of dollars of savings in a typical forest operation: one which might employ 200-300 people at the peak of the season and have a budget of $5-10 million. Unfortunately, I found that although operational planning decisions have become increasingly expensive and decision-making environments more complex over time, the planning technology available to managers has not kept pace with these changes.

THE OPERATIONAL PLANNING PROCESS

Usually the objective of the operational planning process is to produce a plan that satisfies the annual wood supply requirements for the wood processing facilities of a forest products company at minimum cost and an acceptable level of risk. The goals of the plan occasionally may include profit maximization (especially where various products of differing values are involved); return on investment; and forest, wildlife, and recreation management targets. In any case, the planner (usually an operating superintendant or manager) must employ relevant information concerning the wood requirements (quantity, quality, timing) and forest, equipment, human, and other resources available to the operations to devise an acceptable plan.

Wood requirement information is ordinarily provided by corporate management based upon initial market projections for the company's production plants, although detailed scheduling information may come from the mills themselves. The forest management department usually supplies information concerning the specific cut areas deemed acceptable from a forest management perspective. The actual detailed species and product estimates for these areas normally come from an operating cruise, which provides more detailed and accurate forest resource data than is available for forest management planning in general. Where the operating department is responsible for site preparation operations, the specific scarification, planting, and other activities to be undertaken are dictated by management plans, regulations, and agreements formulated by the forestry department. Some equipment data (such as charge-out rates) are ordinarily provided by the mechanical department, whereas machine performance statistics may come from the mechanical department, the accounting department, the operating department itself, and outside sources. The human resources department might be the source of data concerning wage rates, negotiated constraints, policies, and the workers themselves, but it is quite common for operating managers to maintain their own pool of information about workers and contractors. Other statistics, such as those concerning overhead and administrative expenses, may come from the accounting department, corporate management, outside sources, and the operating department itself.

The planner's job is to turn data into useful information, then apply that information to the design of an operating plan that uses the organization's resources to achieve the desired objectives, subject to the known constraints. In a perfect world, this would mean devising a plan that would make optimum use of available or obtainable resources so that all of the harvesting, wood transportation, road construction and maintenance, stand establishment, and support functions are in harmony with each other (and with the plans of other levels of the organization and with the activities of other departments). For the annual operating plan designer, this would mean formulating a plan where the "right" usage of the "right" machines in the "right" systems leads to:

1. the harvest of the "right" products in the "right" areas and the transportation of these at the "right" time to meet mill requirements;

2. the "right" stand establishment activities being undertaken (as defined by the forest management plan and the harvesting plan);

3. the construction and maintenance of the "right" design of road to allow harvesting and transportation and other activities to occur;

4. the "right" support functions being carried out in a way that allows all of the aforementioned to occur in the "right" way.

Of course, the definition of what is "right" in a specific plan depends upon the particular circumstances and the influence of all of the other "good" decisions. For instance, there are several reasons why the best harvesting system for a cut area may not be the least expensive one, even if an operation's only objective is to satisfy wood requirements and minimize costs. After all, because equipment resources are limited, choosing the lowest-cost system for one area means that it may not be available to be used in other areas where the advantages over the next-best systems are even greater. In many cases the rightness of a choice cannot be properly evaluated without an analysis of the effects of such a decision on many other plan elements. A perfect plan would require that managers take a holistic view of operational analysis and planning to integrate the various systems and functions.

In the imperfect real world, managers find that time constraints, lack of information, and deficient planning tools reduce their ability to produce integrated plans. They feel that because of this they are often unable to generate solutions that they would define as "right," even by their own less-than-perfect but realistic standards (Robak and Prasad 1985). The planning process actually employed by forest industry planners typically involves the evaluation of the harvesting function first, followed by determination of acceptable strategies for hauling, road, and support systems. Managers try to ensure that the planned systems are compatible, but they confess that only modest effort is made to integrate the components of the plan. Once a draft plan has been completed, managers may evaluate it to detect problems or investigate cost reduction possibilities, but the time required for such work generally limits its application. Often the analyses end when the resulting plan's cost is within an acceptable range of the previous year's budget. In effect, forest operation managers are not given the tools or the time to produce the better plans they are capable of producing.

PRELIMINARY LITERATURE REVIEW

Because my study confirmed that the lack of good information was perceived to be a problem by practicing forest operation managers, I carried out a literature review to determine what kind of information systems had been developed or proposed to help them. In this review it was found that, although previous attempts had been made to develop computer-based systems to aid forest operation planning, systems aimed at helping solve more than subcomponents of the problem have not been well accepted by their intended users.

In 1969, Carlsson published a description of a system for forest district-level planning of annual wood harvesting, storage, and transportion activities. The model was designed to yield "acceptable" harvesting costs, and a linear programming routine was used to minimize the sum of storage and transportation costs for a given amount of wood. Unfortunately, the model did not allow testing of more than one harvesting system per area and it "optimized" the harvesting separately from the storage and transportation and didn't consider the cost of roads or other support functions.

Goulet et al. (1979) evaluated eight simulation models that purported to handle all activities from stump to mill. In the review the authors concluded that no consensus existed on what constituted a harvesting model's essential elements. They decided that the models were not user-oriented and were unacceptable for practical operational planning because managers could not work with the models interactively but had to rely on the expertise of computer specialists.

Linear programming (LP) was used by Hofle (1971) in Germany to optimize the cost of harvesting small-size wood and by Newnham (1975) in Canada to minimize the cost of annual logging plans. Newnham described his LOGPLAN planning system as one that uses LP to produce a plan that minimizes the direct and indirect cost per cubic metre of a forest operation (not including transportation). Although LOGPLAN was tested in an actual forest operation, it has not been adopted by the industry. Prasad (1985) concluded that an LP approach may provide useful clues to managers about trends and directions in their operations but that LP tends to be too data-demanding and restrictive for day-to-day operational planning and control.

Network analysis techniques for operational planning have been proposed by researchers in Czechoslovakia. Novotony (1971) suggested a procedure requiring the use of a combination of network diagrams with Gantt progress charts and with linear programming. The technique would help plan individual stands but would not help in the essential task of choosing the stands to be harvested.

In summary, the literature review I conducted in the early 1980s led me to believe that nobody had yet developed computer-based tools that were accepted by forest industry managers as aids for producing integrated plans. Nonetheless, the work that had gone on before was useful in pointing out the kinds of operational planning research and development directions that might prove most fruitful.

MODEL AND SYSTEM DEVELOPMENT

Based upon the studies I had conducted (and my own experience), I proposed a model of the operational planning decision process at the camp or district level in non-mountainous Canadian forest operations. The structure of the model was based upon the decisions that were deemed essential to the planning process, the information required to properly make those decisions, and the combination of data and models that could be used to yield the necessary information. The basic principle underlying my approach to the development of the model was that the various components of the operational plan must be linked so that all of the quantifiable effects of a proposed planning decision could be measured. I proposed that this linkage would be primarily accomplished by relating all decisions to their effects upon the entire budget. Since then, I have concluded that other measures of overall efficiency and effectiveness (such as profit or product volumes and costs) may be equally important in determining the rightness of a decision.

To confirm that this philosophy was valid and, if so, to transfer the technology to industry, I developed a prototype microcomputer-based planning system in collaboration with a major forest product company in eastern Canada. Each of the district operation managers of that company was required to plan the harvest and delivery of approximately one-sixth of the 1 700 000 solid cubic metres of various (almost 50) products for the corporation's many processing plants and raw wood product customers. Managers were also required to select the road construction and maintenance systems and the support functions that appropriately fit the harvesting and delivery plan.

To apply my model to their problem, I decided to adopt an approach to planning model formulation that involves the application of decision support system (DSS) philosophy. Conceptually, decision support systems are intended to support the kinds of unstructured or semistructured decision-making processes that typically confront forest operation managers. They are designed to use appropriate models to process data into real information: information that could be used in the relevant decision-making situation. The computer-based system is considered to be only part of a larger system that includes a manager's own experience, intuition, and thought processes.

The first prototype, called OP-PLAN, was completed in 1984 using the DSS approach to needs analysis, design, and development (for more information on how the DSS approach was applied to this problem, see Robak 1984; Prasad 1985). Strengths of the DSS approach include its emphasis on a high degree of user involvement in the design and development process and the use of prototyping as a deliberate system development strategy. Unfortunately, I had found it difficult to meet often with the intended users to get their views on details, and the development language used (BASIC) is not a good prototyping tool. The lack of adequate consultation meant that although the prototype system did everything that the managers had requested (and more), it still lacked specific capabilities that were required to support the decision-making environment of that particular organization with its special needs. The inadequacy of the development language hindered the process that should have produced newer and better versions of the system at the accelerated rate necessary to maintain managers' interest. Furthermore, when it came time to implement the preliminary DSS, the company did not supply their managers with the kind of support that would make start-up and directed prototyping work properly.

Although the test system was not sufficiently powerful to satisfy the company's planning needs, the reaction of the client managers to the prototype confirmed that the model of the operational planning decision process could be valid. As a result of this experience I founded a company that would be able to provide development and implementation support to future clients and determine the system development technology needed to produce a new-generation OP-PLAN.

OP-PLAN VERSION 2.0

Upon studying the problem we decided that to improve OP-PLAN and make it maintainable over the long term we needed much better development languages and supporting tools. It was apparent that if the model was going to be properly applied, the system should be able to handle all of the data generated during the planning process. As well, the development technology would need to be able to support a very accelerated iterative system design, development, and validation cycle. We began by using dBase III (from Ashton-Tate) and Clipper (from Nantucket) on a PC-XT. These packages belong to a popular family of development tools in the microcomputer environment, but we decided after considerable effort that the resulting product would be unacceptably slow for forest operation managers. We did confirm, however, that an approach based upon good data-base management system (DBMS) technology was essential.

We subsequently spent a good deal of time and effort trying out various software and hardware combinations to determine what would help us meet the needs of the industry. This process was complicated because technology in both areas was developing at a tremendous rate. We were constantly forced to spend money and time sifting out what new software products could really do as opposed to what their promoters said they could do or would do "in the near future." On the advice of a consultant who worked primarily in the mainframe and mini environment, we decided to evaluate several development products that were popular with big-system developers and had been redeveloped for microcomputers. Unfortunately, we wasted considerable time and money to find out that these packages might be adequate in the mainframe market but that they weren't good enough for us. After frustrating attempts to develop a system using a self-touted "fourth generation language" that never delivered on its promises, we decided to go back to using a new and faster version of Clipper to develop an improved OP-PLAN that would work in the (increasingly common) PC-AT or 80386 microcomputer environment. The language (a dBase III + code compiler with language enhancements) has the DBMS and dialogue capabilities that the OP-PLAN system requires and is quite capable of working with the development tools that third-party suppliers sell for the dBase III + environment.

The newest version of OP-PLAN is true to my original vision of an operational planning tool that can help managers to plan more holistically. It allows managers to plan the harvesting, wood transportation, roads, and silviculture in cut areas for each camp in a district, the main and secondary roads at that level, and the support functions (overheads) at the camp, district, and company levels. Wood costs are calculated and presented at the machine, system, function, area, camp, district, and company levels. The harvested and hauled volumes and costs of specific products can be viewed at various relevant levels. These product costs are based upon accurate estimates rather than system averages. Managers are also able to see the effect of planning decisions on overall machine hours or other logistical information. The effect of changing machine usage or productivity, machine types, systems, products, and cut areas can be examined in seconds, so that plan design and sensitivity analysis capabilities are enhanced. A section was recently added that greatly increases a manager's ability to conduct company-wide sensitivity analysis by calculating the effect on the entire plan of a change in the cost or usage of a machine type. Another new segment automatically calculates the harvesting costs of each available harvesting system in each cut area that has not been manually planned.

OP-PLAN APPLICATIONS IN INDUSTRY AND EDUCATION

Although each implementation of the OP-PLAN DSS must be custom designed for a specific organization and its planning environment, the core of the system is founded upon my model of forest industry operational planning decision processes. The favorable reviews that the system has received from practicing managers and applied researchers in Canada, the U.S., and from overseas suggest that the model itself may be sound. Ultimately, however, the only worthwhile validation of my model would be the confirmation that OP-PLAN actually helps managers make better planning decisions.

The first opportunity to view the results of the implementation of the new OP-PLAN system in an industrial situation was made possible when a Quebec-based forest products company purchased a license to the software in 1988. Interestingly, at the time that the company agreed to buy OP-PLAN, its planning environment was relatively uncomplicated; however, the management of the company was aware that its operations were on the verge of some major and fundamental changes that would greatly complicate the planning process. Because this company prides itself on running a lean operation, management knew that it would not be possible to hire the staff that such a decision environment would normally require. The managers decided that the only way they could properly plan and control in this more challenging situation was by using the technology necessary to provide managers with the information they needed to make good and timely decisions.

In the past few months, high-speed modems and special communication software have been used to quickly and inexpensively provide custom modifications to OP-PLAN to suit the client's particular situation. Unfortunately, because their planning environment has become more complex at a faster rate than was originally envisaged, the operation managers have not been able (at the time of the writing of this paper) to spend the time necessary to complete their version of the DSS. They have not yet used OP-PLAN for operational planning, so I can't confirm or refute the validity of my model on the basis of its utility in a real planning situation. All that can be said at this point is that the customization that the managers have demanded will not result in a package that is essentially different from the basic core of OP-PLAN.

I have used various versions of OP-PLAN for the purposes of teaching operational planning and control at the University of New Brunswick for several years. In a paper presented at a IUFRO (International Union of Forestry Research Organizations) world congress (Robak 1986), I stated that I believed that the system was useful for the following:

1. improving students' abilities to understand and (where appropriate) apply previously learned analytical techniques and concepts such as linear regression, linear programming, and sensitivity analysis;

2. increasing their understanding of the interdependence of decisions made in an organizational setting;

3. increasing students' understanding of the difference between data and information and their knowledge of operational planning information requirements;

4. encouraging students to develop simple, but effective, computer-based techniques for the analysis of such information;

5. establishing an appreciation of the fact that not all information necessary for decision making is quantifiable;

6. engendering an appreciation of the necessity for a holistic approach to decision processes; and

7. fostering a deeper awareness of the benefits and limitations of computer applications.

In summary, "the DSS helped to create an environment which facilitated students' understanding of integrated planning, data and decision interdependence, and the place of nonquantifiable information in managerial decision-making," and "the entire approach fostered greater interest in applying computer-based techniques in future managerial decision-making situations" (Robak 1986). Most recently, OP-PLAN has been installed at the forestry school at the University of Moncton. Other universities in Canada, Ireland, Sweden, and New Zealand have also expressed interest in using it for teaching purposes.

THE FUTURE

In recent years I have conducted various research projects and collaborated with others in an effort to strengthen the links between operational and strategic or longer-term planning decision processes. I am currently working on a project that would use OP-PLAN, FORPLAN, and a geographic information system (GIS) together to help forestry organizations ensure that their long-term planning takes into account operational realities and that their operational planning conforms with the long-term forest management plans. A doctoral candidate at the University of Laval has recently instituted a research project in which he intends to use OP-PLAN to help define the decision process aimed at improving system selection. In 1989 I will begin a series of collaborative projects in Ireland, Sweden, Australia, and Japan in which OP-PLAN will form the operational planning foundation of integrated planning decision processes. In fact, our research team in Japan will study the possibility of developing a "mega-system" that integrates OP-PLAN with harvest scheduling, inventory, and road network design tools for the Japanese forestry service.

The current emphasis in new design and development work on OP-PLAN is in the area of integration. It is probably safe to say that OP-PLAN's benefits as an operational planning tool will increase when it is tied into an organization's GIS and other major information and decision support systems used for corporate strategic planning, capital and operational budgeting, accounting, forest resource planning, inventory analysis, and equipment planning and control.

SUMMARY

Operational planning in most forest operations is a complex task that if done improperly can result in major financial losses. Most models that have been developed to help managers plan their operations have tended to concentrate on specific, narrow parts of the larger planning task so that integrated planning of the entire operation was not facilitated. Information gained from studies of operational planning techniques employed in the early 1980s in the Canadian forest industry was used to formulate a model of planning processes. This model formed the basis of design for a forest operation planning decision support system, called OP-PLAN, that is being implemented by a Canadian forest products company. The OP-PLAN system has also proven to be a valuable teaching tool and is currently being used as a research instrument by various groups interested in integrated planning. It is expected that future development of the system will concentrate on enhancing its ability to function as part of an overall integrated planning system.

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GIS AND WOOD SUPPLY ANALYSIS

W.H. Lougheed
Weldwood of Canada Limited
Hinton, Alberta

ABSTRACT

Geographic information systems complement wood supply analyses in providing a means to aggregate stands based on both biological features and geographic location. A Haulcost System was developed that uses generic ARC/INFO and custom software routines to calculate timing of access (accessible area) and haul costs for individual stands. Strata for wood supply analysis, resulting from alternative road networks or construction timing, are then derived. A case study encompassing a 1000 km^2 area in northern Ontario was used to evaluate the Haulcost System with respect to sustainable harvest levels, production costs, and timber management strategies. Three access alternatives were examined, which included perfect access to the forest (control), the existing road network (Network 1), and a network designed to provide maximum access per kilometre of road constructed (Network 2). Wood supply analyses for the three alternatives found significant differences in maximum sustainable harvest levels, harvest schedules, production costs, and treatment intensities.

INTRODUCTION

Geographic information systems (GISs) are commonly used in determining the area-related input for wood supply analysis. The objective of the project was to determine whether a technique to describe more accurately the area-related input would be of benefit in evaluating wood supply from a forest area. Wood supply analyses that assume perfect access to a forest implicitly require that each hectare of the forest be accessible to implement the harvest schedule. Recognizing the operational reality that road network design and construction timing define access to a forest, the Haulcost System was developed using GIS technology to evaluate the accessible area and calculate haul costs for stands. Stratifying the forest according to haul costs and defining accessibility constraints resulted in more accurate area-related input to the wood supply analysis.

This paper will first describe the Haulcost System used to calculate haul costs and accessible area for a case study forest. Results of wood supply analysis performed using both perfect access and constrained access scenarios are compared. Conclusions are then made regarding the benefits of incorporating the Haulcost System in wood supply analysis. A more complete description of the Haulcost System can be found in Lougheed (1988).

HAULCOST SYSTEM ANALYSIS

The Haulcost System was implemented on the ARC/INFO GIS (Environmental Systems Research Institute 1987) using both custom programs (Fortran and INFO) and ARC/INFO macros. The analysis resulted in the haul cost ($/m^3) and time of access attributes for each stand in the forest. The following steps describe the Haulcost System:

1. Create road coverages. Coverages were created depicting actual and planned roads for the forest area during specified periods in the future.

2. Calculate minimum-distance line coverages. Line coverages, one for each period in the future, were used as the basis for calculating haul costs. The line coverages contain all road arcs and the shortest-path arcs between each accessible stand and the road coverage for that period. Accessible stands were defined as those stands within a "search tolerance" of the road network.

3. Calculate arc travel times. Travel times for each road arc and shortest-path arc to a stand were calculated as a function of haul speed (road class) and arc length.

4. Calculate cumulative travel times. The ARCALLOCATE utility (Environmental Systems Research

Institute 1987) calculated the cumulative travel time from specified forest entry points to each arc in the line coverage.

5. Calculate haul costs. Haul costs were a function of the time required to make a round trip between the mill and the stand and the hourly equipment and labor costs. An INFO program used the cumulative travel times to calculate the haul cost for each accessible stand.

6. Calculate timing of access. Timing of access was defined as the period in which the stand reached its minimum haul cost. The haul cost and timing of access for each accessible stand were transferred to the forest inventory file.

The Haulcost System was used to evaluate two road networks for a 1000 km^2 case study forest, part of the Great Lakes Forest Products Dog River-Mattawin Forest Management Area in northern Ontario. Network 1 was the existing road network and proposed road construction, and Network 2 was a fictitious network designed to access the maximum land area with the least amount of road construction. Figure 1 shows the accessible area by period for the control and both networks; Figure 2 shows the area by haul zone during the last period. These haul cost stratifications and accessible areas were used for the area-related inputs to the wood supply analysis.

WOOD SUPPLY ANALYSIS

The wood supply analysis was performed using Timber RAM (Navon 1971). Two problem formulations were used to evaluate sustainable harvest levels and production costs. First, volume maximization determined the maximum harvest level (productivepotential) of the forest. Secondly, cost minimization determined the minimum production cost for a specified harvest level. A production possibility curve can be generated for each road network by a series of simulations that determine production costs at specified harvest levels.

RESULTS

The results of 29 Timber RAM simulations are shown in Figure 3. The control assumed perfect access to all stands in the forest and an average haul cost of $7/$m^3$. Using the results of analysis with the Haulcost System, networks 1 and 2 included access constraints and three haul zones: $5/$m^3$, $7/$m^3$, and $9/$m^3$.

Productive potential was greatest for the control because of the larger forest area resulting from the perfect access assumption. Network 2 shows a higher potential than Network 1 because of an accelerated road construction program and greater accessible area in each period.

Mill gate costs for the control show the effects of assuming an average haul cost. At lower harvest levels, mill gate costs are higher because the network alternatives harvest primarily from the $5/$m^3$ haul zone. At higher harvest levels, the mill gate cost is cheaper because the networks must harvest from $9/$m^3$ haul zones to meet the harvest level. Network 2 is cheaper at given harvest levels than Network 1 because of an accelerated road construction program and greater accessed area in each period.

Ten-year harvest schedules for the three scenarios at the 80 000 m^3/year harvest level reflected restrictions imposed by access constraints. The control had harvest occurring in eight stand classes, Network 1 in 41, and Network 2 in 26. The control, in assuming perfect access to all stands in all periods, scheduled the harvest in the most cost-effective stand classes. The networks required more stand classes to meet the harvest level because of the smaller forest area accessible during each period.

CONCLUSIONS

Results of the three wood supply analysis scenarios show that the control, in assuming perfect access and an average haul cost, had a significantly higher production potential (nearly 50% greater than Network 2) and averaged production costs. Additionally, the harvest schedule for the control was found to require harvest in areas that were not accessible and therefore could not be implemented.

In conclusion, stratifying the forest according to haul costs and defining accessibility constraints resulted in three primary benefits of evaluating wood supply from a forest. First, a more-accurate indication of the productive potential from a forest area, given a particular road network, is obtained. Secondly, the treatment schedule required to realize the harvest level would be physically possible to implement. Third is the ability to compare alternative road network designs, or access alternatives, with respect to sustainable harvest levels and production costs.

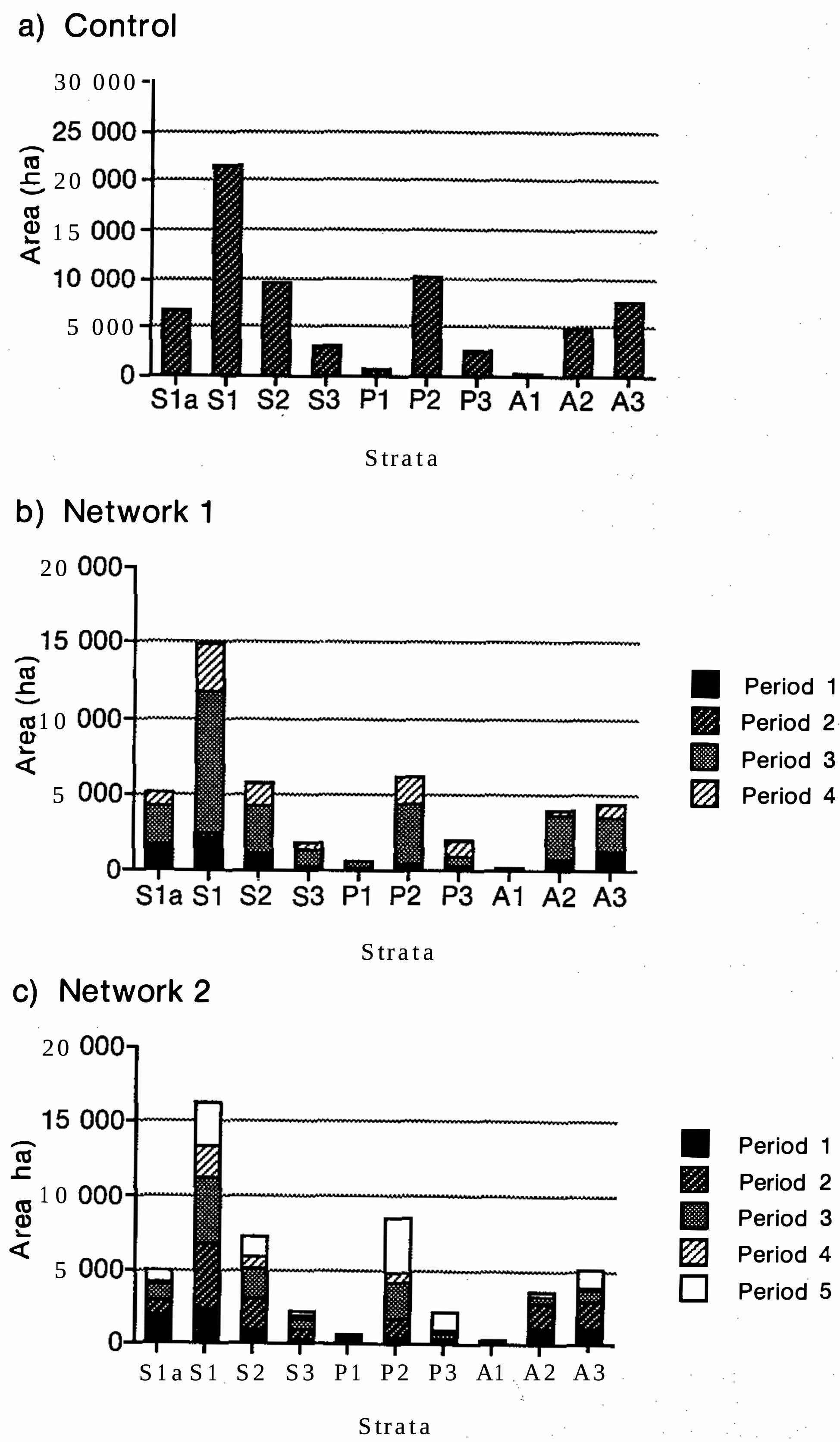

Figure 1. Accessible area by period.

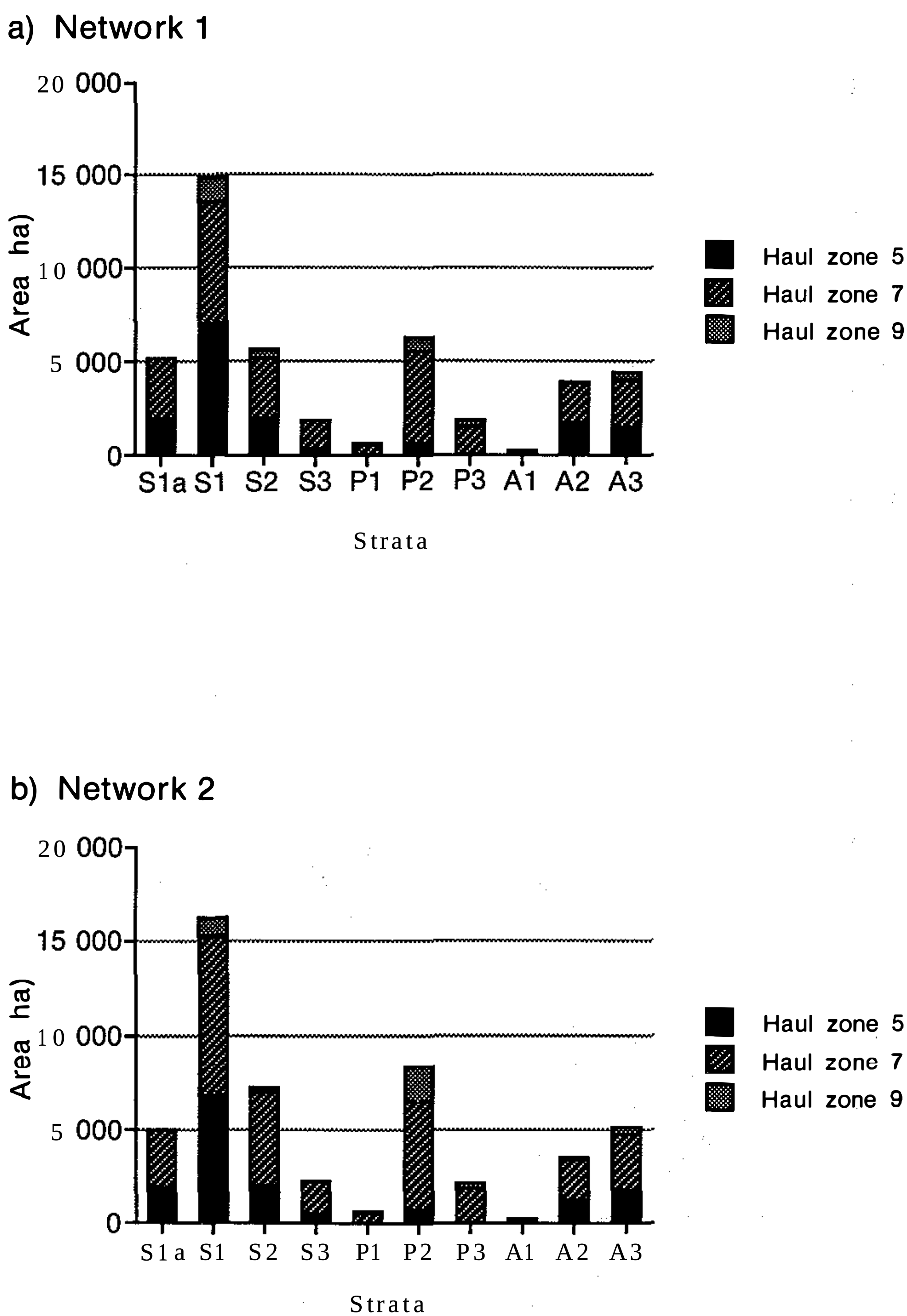

Figure 2. Area by haul zone.

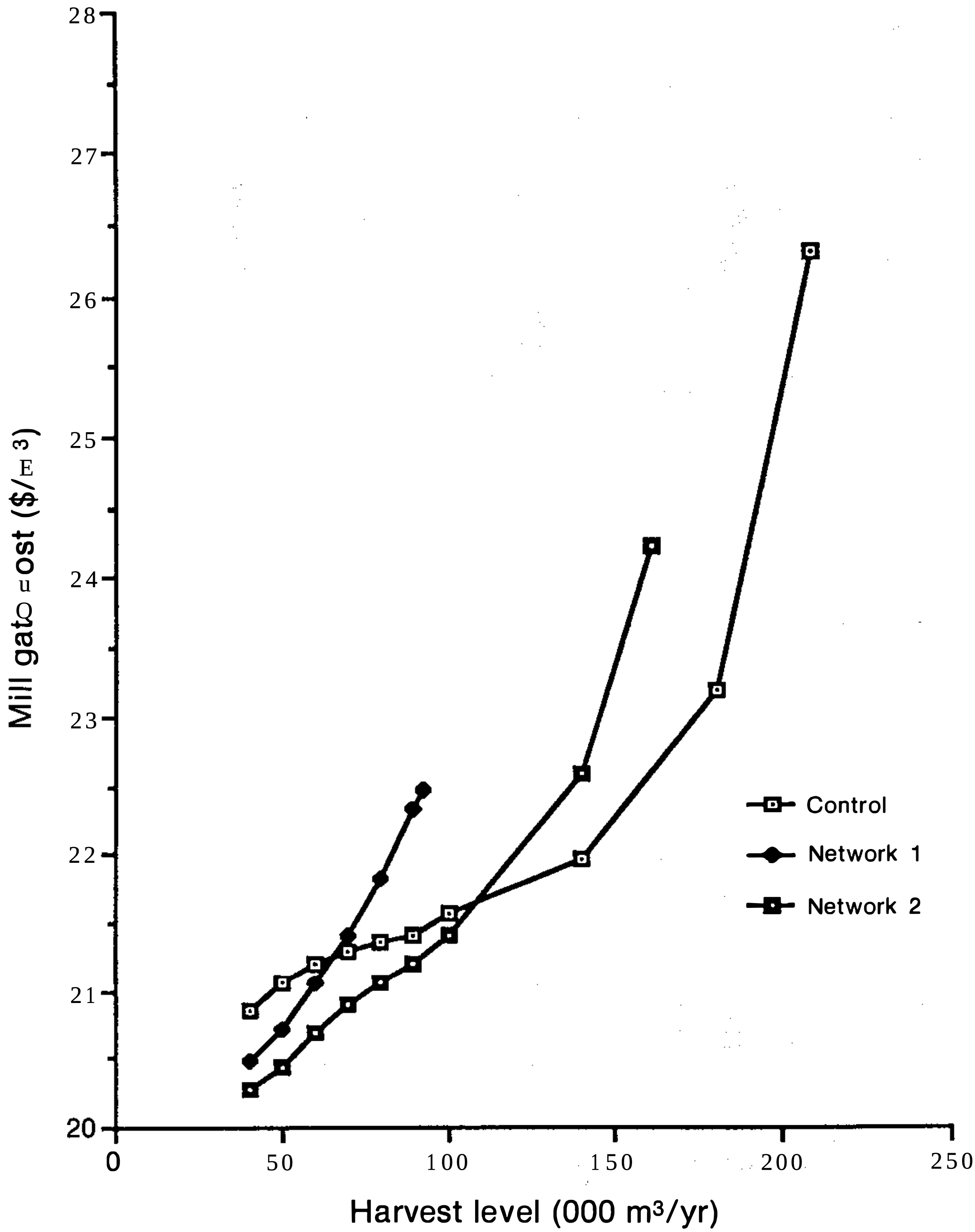

Figure 3. Production possibility curves from Timber RAM simulations.

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QUESTION AND ANSWER SESSION

Question for Dave Depta by Jim Beck:

Yesterday, Don Reimer was talking about what's needed for growth models, and he indicated he thought the trend in the future was for distance-dependent growth models. Could you comment on the particular growth models you use? Are they distance-dependent, distance-independent, or what?

Dave Depta:

We don't use distance-dependent models in any of our forecasting. We do use a lot of stand-table model projections by different size class. So we use stand-table models in their traditional way. The difficulty with distance-dependent models is that collection of the basic data to drive them in the first place is a significant obstacle. Unless you're willing to collect a lot of statistics, like Poisson distribution statistics, or get involved heavily in stem mapping, we just really don't think it's worth the trip in terms of the expenditure associated with going that particular route. Some day, maybe. But in my own mind, the technology is not there to make it particularly practical today.

Question for Ken Runyon by Teja Singh:

We had a lot of debate on free trade recently, and we have free trade with the U.S. What sort of impact will it have on the national wood supply, and how are you going to take care of it in wood supply modeling at the national level?

Ken Runyon:

I don't see that there's likely to be too much of an effect of free trade on wood supply. We've had essentially free trade with respect to forest products in the past, with the exception of some of the higher value-added products such as supply wood and some other very specialized products. Where we have free trade now, we have had it in those areas: lumber, pulp, and so forth. So I don't see too much impact there. With respect to how that might impact on our modeling approach, I think that we anticipate maybe being able to look at the change in exchange rate, for example, and how that might affect end-product demand and, therefore, roundwood demand. If you look at a tariff effect, for example, presumably with free trade we won't have increased tariffs. But let's take lumber right now: instead of 15%, let's say it's 25%. We know that it's likely to make the lumber price more expensive in the States. Housing is going to be more expensive; therefore, presumably there'd be a lower relative demand for roundwood. I don't think it's too critical, but we recognize that potential need, though.

Question for Cindy Pearce by Hamish Kimmins:

A statement, a concern, and a question for Cindy. Statement: I'm very impressed by the variety and elegance of the various planning tools that are being presented here, and I'm sure we'll hear some more very good ones this afternoon. I think, certainly, modeling is going to be helping forest management greatly in the future as a result of these. My concern: It seems that the modeling activities are occurring in relative isolation from each other, and I see a growing need for linkage between different modeling activities. Very elegant modeling in the economics area or in the yield projection area that totally ignores environmental impacts, other resource constraints, and long-term productivity questions, in spite of the elegance of the modeling, may be totally unbelievable. I think we foresters really need to start thinking about the role of the environmental movement around the world in controlling what we do. If we don't produce environmentally believable planning tools and planning projections, we're going to have a lot of forest areas and a lot of forest decisions taken away from us. It's happening around the world. It's starting to happen in B.C. So the question to Cindy (I very much enjoyed your presentation) is: How are you going to arrive at the probabilities in your model when often we just don't have the experience?

Cindy Pearce:

That's a constant question, and because we haven't implemented the model, we haven't actually gone that second step. I can say that, number one, I'm one of the people who provides some of the probabilities in the base case or default data base because I have had a fair amount of experience looking at success rates, both in terms of reported survival rates and in terms of walking around in the bush. The advisory committee members that we're working with, who are all silviculturists and operational foresters, have expressed a desire to be forced to sit down and think about the probabilities and to provide those numbers. In terms of implementation, the strategy we intend to take at this stage is to work with a single individual for the first implementation to provide default data. After that, when we start working on, say, public forests in B.C., where there are a number of operators and a number of perceptions about what the data should be, we would work with an expert committee. Probably we would not be able to come up with average values but would identify upper and lower bounds and then do sensitivity analysis around those data bases. That's going to be a problem with the model, there's no question, but I think we have to explicitly recognize that those values do affect the outcomes. By ignoring them, that's probably a higher cost.

Dave Depta:

I have the same problem in that productivity, for instance, is a very important driving force in terms of wood costs and so on, and exactly the same thing can be applied. I guess the point is, are we better off than before? That's the important thing. If you can still use the same data and do more things with it, then, certainly. One thing I found out is that the company I worked with originally all of a sudden is doing studies (time studies, cost studies) it had never done before, because it could use the data. The other thing is, even if you've got a pretty shaky, fuzzy set of data, you can still do sensitivity analysis as you described and see, "Well, is that bad?" How much effect is it going to have on the thing? That's a very important thing to recognize. It's not that the data's lousy, so let's forget it. We don't have a choice; we've got to make decisions.

Question for Cindy Pearce by Imre Bella:

It was most impressive to see this formal structure presented today. My first question is, is this going to be available as a public domain effort? I presume it would be, because it is supported through Forestry Canada.

Glen Manning:

Let me answer that one first. We have assigned the patent rights for this to the Canada Patent Development Corporation, because we think it is patentable technology. They are busy negotiating a royalty arrangement with McDaniels Research. Now, I'm not supposed to say this, but I'll say it anyhow. I've insisted that it be available in the public domain to public agencies. I'm sorry, industry, you're going to have to pay for it.

Question for Cindy Pearce by Imre Bella:

The other question I have is related to the data needs. Particularly, how are you going to implement this program when the people out in the field have to select some kind of growth and yield predicting mechanism? That is going to be a pretty risky business. I just wondered whether you could elaborate on that or whether you're going to have somebody from Victoria or wherever provide that kind of background every time or at least in the initial stage to get the program going.

Cindy Pearce:

This is a Forestry Canada prototype program. At the moment, we have a responsibility to carry out a case study. That case study is on coastal Douglas-fir management, and the yield curves have come from Stephen Smith, who is a consultant in the Vancouver area. The yield curves are approved by the B.C. Forest Service for TFL [tree farm license] modeling, and so we've implemented those in analyzing a TSA [timber supply area]. The next project that we have when the thing is working—remember, it's not working yet—is hopefully with a company in the northern part of British Columbia on a TFL, where they have their own yield curves basically derived from work with lodgepole pine in B.C. and Alberta, and the TASS [model] projections out of the Ministry of Forests. I maybe misled you by saying that the forester would input the data. I think it's important to say that the model would hopefully always be provided with default data that the forester has the opportunity to change if he disagrees with it. The default data is really important. It's much easier for people to respond to a set of numbers than to respond to a blank screen. I also should comment in terms of Hamish's point earlier about the integration of modeling. There are three major modeling efforts going on in B.C. alone, right in Vancouver, on the silviculture decision element, and trying to keep those together has been difficult. We are working with a FERIC group to come up with our product values because they've spent a lot of time defining that data, and we are working with the ESSA [Consulting Ltd.] and FEPA [Forest Economics and Policy Analysis] group, who are working with the Ministry of Forests, and using the same inventory data base as much as possible. The coordination is critical, but it is definitely time-consuming.

Question for Cindy Pearce by Tom Erdle:

I'm not entirely clear. Is the intended use of this model to provide guidance for decisions about existing cutovers and what should be done with them, or is it to guide the development of a regime of silviculture that would be implemented over some longer period of time?

Cindy Pearce:

The initial contract's terms of reference dealt with existing disturbances and treating those stands. But you can implement the same information—assuming that you perceive the harvesting treatment to have similar effects—to analyze the type of regime that should be implemented over time. Our first application with a company will involve reprogramming the model to integrate the harvesting treatments, selection of silvicultural system, and harvesting method and its effect on outcomes and costs, etc. So, at the moment, it's designed specifically to analyze what to do in a series of treatments on a specific stand that's already disturbed. But you can extrapolate that information in terms of what to do before you start, as well.

Question for Cindy Pearce by Tom Erdle:

So when you take the forest-level perspective that you described, how do you reconcile the fact that the desirability of this year's treatment really depends on what you intend to do elsewhere next year, or the year after, or the year after that?

Cindy Pearce:

That's dealt with by iterating through the yield analysis approach. You identify your first option treatment, reprogram the status quo treatments and the yield analysis to depict those treatments, and then identify the next best treatment level and implement that, and go through an iterative process. So you can incorporate the effects of treatments on various areas in the forest through that approach at the forest level, not at the stand level though.

SESSION IV:

MODELING IN OTHER RESOURCE SECTORS

USING HYDROLOGICAL MODELING IN FORESTRY

P.Y. Bernier
Laurentian Forestry Centre
Ste.-Foy, Quebec

ABSTRACT

Forest managers must look at water from two perspectives: as a resource for downstream use and as an essential element for forest survival and growth. Hydrological modeling can help the forest manager protect the water resource for downstream use. Hydrological concepts, whether or not in models, can also be put to many applications in forestry. Determination of inherent site productivity and of "plantation windows," as well as the management of tree water demand and of soil water supply through modifications in block size, shape, and orientation are examples of direct applications of hydrology to forestry. Most models cannot be used for management purposes because of their complexity and their demanding input needs. A procedure for determining the effect of changes in forest cover on water yield called WRENSS has been derived from water balance models and is an excellent example of how models can be simplified and made usable on a day-to-day basis by forest managers.

INTRODUCTION

There are two ways to view the relation between forestry and water. The first is to view water as a resource in its own right, usually intended for downstream use. The second is to view water as an element essential for forest growth. Traditionally, the "water as a resource" view has been prevalent, as reflected by the fact that this presentation was put in the "other resource sectors" portion of this symposium. In this view, the relation is one of parallel management, in that the actions of forestry can influence the quantity, quality, and timing of streamflow. Thus, the management of trees and water are inextricably tied together through the action of man on the environment, and those ties often place the management of these two resources in conflict with one another. Models are important management tools in this context because they assess the impact of forestry operations on the water resource.

Trees are water consumers, however, and the level of equilibrium between water demand and water availability is often critical for the survival and growth of trees. In this view, the relation is one of dependency in that forest management can influence, and is influenced by, the tree's water demand and the site's water availability. The study of the water available to trees and the water consumed by trees thus should not be classified off-hand as an "other resource sector" because many hydrological concepts can and should be used to improve forest management practices. We will see later that modeling efforts currently under way attempt to improve forestry practices using hydrological knowledge.

MODELS AND HYDROLOGICAL MODELING

I will not dwell on what a model is, since by this time you will have heard many definitions from previous speakers. I would just like to add that a model is not necessarily an impressive assemblage of computer code. One-line equations that present an empirical view of reality are also models in their own right. And, often, complex computer models are just fancy representations of such one-line models!

The term "hydrological model" can be loosely defined as a model centered around one or more of the phases of the hydrological cycle. Thus, snowmelt models, evapotranspiration (ET) or microclimatic models, and groundwater models are all hydrological models. This definition is rather broad; because of the importance of water in the environment, many models incorporate some method of accounting for water without being formally recognized as hydrological models.

Most hydrological models are process-based. Processes represent physical actions taking place at a specific location over a specific amount of time. Snowmelt, for example, is a well-modeled process (e.g., Leaf and Brink 1973a; Anderson 1976; Price and Dunne 1976; Smith et al. 1976; Obled and Rosse 1977; Weismann 1977; Cooley 1986). Infiltration, or the movement of water in the saturated or unsaturated portions of the soil, is also well modeled. Expansion of a one-time-step simple-process model can go in many directions. The model can be expanded in time to simulate the process over a longer period or expanded in space to simulate the spatial variability of the process over a hill slope or a basin or both. Process models can be linked or layered to represent more complete pathways of water movement, say from snowmelt, to soil percolation to streamflow, or to represent a more complete picture of yearly cycles in water pathways, with, for example, snowmelt in the spring and ET in the summer. The separation between evapotranspiration models, snowmelt models, water yield models, or other hydrological models is often a matter of degree of representation of the different processes.

USING HYDROLOGICAL MODELING IN FORESTRY

Traditional Applications: In-stream Effects

As I mentioned in the introduction, there are two ways of looking at water: as a resource for downstream use and as an essential component for forest survival and growth. First, in the realm of downstream use, the influence of forestry can be felt on the quantity, timing, and quality of the water in the streams. In Canada, except for a few municipal catchments, there is currently no river basin where forests are managed specifically for the enhancement or the protection of the water resource. Forested lands are prime suppliers of surface waters, however. For example, Laycock (1965) computed that for a moderately dry year, 95% of the flow in the South Saskatchewan River was generated in its forested headwaters covering only 20% of the basin area. It is therefore understandable that the protection of the water resource should be at least an implicit constraint in the management of the timber resource. Models exist, or are being developed, to help the forest managers in this task.

1. Water Yield

Forestry operations can dramatically influence water yields of a basin. In experiments conducted in Alberta (Swanson and Hillman 1977; Swanson et al. 1986) and in Colorado (Bates and Henry 1928; Troendle and Leaf 1981), the annual water yield increase per hectare clear-cut ranged from 250 to 1800 m^3. The smaller increase was obtained from one 80-ha clear-cut, while the highest increase was obtained in Colorado by using 1-ha cut blocks. Partial clear-cuts with 10-20 ha blocks in Alberta have produced 800 m^3 of extra water per hectare annually. The yield increase is the result of reductions in losses through transpiration and losses through evaporation from intercepted snow following the removal of the forest cover. The effect of cut size on yield increase is due to wind and shading effects. Small cuts trap snow and reduce its evaporation. Large cuts expose the snow to wind-driven transport and evaporation. The effect of the cut on water yield declines gradually over the next 10-30 years as the forest grows back.

Models that compute annual water yields are called water balance models, meaning that they are simply models that keep track of inputs and outputs of water into a system. In their simplest form, water balance models include a procedure for computing evapotranspiration (ET), one for computing snowmelt (at least for our snowy regions), and a soil-defined storage unit that "overflows" into a "water yield" bucket. One widely used water balance model developed by Leaf and Brink in 1973 is now the base for the WRENSS procedure, which will be discussed later in this presentation.

2. Streamflow Regime (Timing and Magnitude)

Forestry operations also affect the distribution of streamflow over the year. Low flows are increased through increased soil reserves. Snowmelt runoff is advanced or retarded depending on the exposition of the hill slope. Peak flows are increased or unchanged depending on the source of water (rain or melt) and on the magnitude of the event. A good example of these effects can be found in Swanson and Hillman (1977). Forestry effects on spring and summer flood peaks and on summer low flows are often at the heart of disputes between forestry companies and local residents. In British Columbia, for example, there is substantial concern about the effect of forestry on the flood flows that accompany rain-on-snow events. The modeling of forestry effects on streamflow regime is probably the best way to avoid or solve these conflicts.

Models that compute streamflow usually start off with a water balance component that computes hourly, daily, or weekly amounts of "nonevapotranspired" water that is available for streamflow on the basin. Streamflow models take these amounts and transform them through more or less complex routing procedures into actual streamflow at a particular point in a stream, usually a gauging site. So, in addition to climate- and vegetation-related inputs, streamflow models require information on topography, physical properties of soils, and even channel morphology. In many instances all of these extra variables are rolled into a few (or many) adjustable parameters whose values are obtained by calibration. One such streamflow model currently under study at the Northern Forestry Centre is the HSPF model, a model developed at Stanford University in California.

3. Water Quality: Migration of Sediments

The impact of forestry on erosion and sedimentation is as varied as the terrain covered by forestry operations. How much erosion occurs over a clearcut area depends on many factors, including topography, soil type, precipitation regime, the type of forestry operation, and its location with respect to stream channels. Erosion is detrimental to both water quality and site quality, and the estimation of erosion potential of forestry activities has been part of the objectives of numerous research programs in the prairie provinces (Swanson et al. 1986; van der Vinne and Andres 1989) and elsewhere (Ursic 1986; Burt et al. 1984; Rice et al. 1979). In general, it has been found that the worst erosion problems are usually associated with poor road construction practices. Models have been developed to help predict the effect of forestry on the rate of erosion from logged areas.

Unlike water balance models, erosion-sedimentation models usually proceed on a storm-by-storm basis, because the erosion caused by a storm is unaffected by previous rainfall. Forest hydrologists have generally modified Wischmeier's Universal Soil Loss Equation (Wischmeier and Smith 1960), an agricultural erosion model, for forestry conditions. One such adaptation is that by Burns and Hewlett (1983). Another, far more complex one, is offered by Warrington et al. (1980).

4. Water Quality: Migration of Chemicals

The ongoing controversy surrounding the use of herbicides in forestry clearly outlines the need for methods to predict the environmental fate of chemicals once they are sprayed or applied over a basin. Unfortunately, chemical routing models are probably the most complex of all hydrological models. Such models must include a water balance model to simulate the quantity and timing of water entry into the soil and a complete soil water routing function as in the best of streamflow models. Chemical routing models must also incorporate a component that keeps track of chemical reactions between the compound of interest and the soil, including degradation into secondary components and retention on exchange sites. This is an area where modeling is still struggling to represent what is actually happening in the field.

New Applications: Hydrology and Tree Growth

As I said before, water is not only a resource that has to be managed in parallel to the timber resource. Water is also a key factor in the growth and survival of trees, as are light and nutrients. In fact, in many parts of western North America, water availability with respect to water demand is probably the most limiting factor for tree survival and growth. There are many aspects of operational forestry that can benefit a great deal from the application of hydrological concepts, whether through modeling or not. I will illustrate below three such applications.

1. Evaluating Site Productivity

The productivity of a site is often determined from measurements made on the stand already existing on the site; however, the growth pattern of the stand has already been influenced not only by the inherent productivity of the site but by many other factors like initial density of the stand, fire, insect and disease outbreaks; and competition from other plant species. As mentioned before, in many parts of western North America, including the Rocky Mountain foothills, water is the most limiting factor for tree growth. By linking a water balance model to a tree growth model, one can therefore estimate the inherent potential of the site for growing timber.

Applications for such a model go far beyond that of regular site index classification. Users can compute the growth potential of currently nonforested sites, compare sites stocked with different species, or even estimate the effect of a summer drought or a snowless winter on annual wood increment. Such models already exist. A good example of this type of model is DAYTRANS (Running 1984a, b), which computes daily water requirements of the tree (Douglas-fir), the soil water supply, and in a feedback loop, the effect of the water supply on photosynthesis and transpiration.

2. *Determining Plantation Windows*

Another application of hydrological modeling in forestry is the determination of planting windows. Using a water balance model for cutover sites, and linking such a model to seedling water requirements, one can compute whether or not a seedling will survive if planted. With such a model, and using many years of data, planners can determine which period of summer is on average more conducive to successful planting on different sites. Real-time computations can also be carried out to determine if conditions are right for planting. An example of such a modeling effort is given by Childs et al. (1987).

3. *Planning Cuts to Maximize Water Available to the Trees*

This last application is one for which there exists no formal model. The survival and establishment of seedlings and the growth of trees is largely controlled by how the plant's evaporative needs are matched by the availability of water. By altering the size, shape, and orientation of clear-cuts according to their aspect, exposure, and the height of surrounding trees, we can modify both water demand and water supply through increased snow-trapping efficiency, protection from wind, and shading. Other factors such as roughness of cuts, choice of species, and competition also influence water availability and demand. Through models we can study the interactions of all these parameters and specify site-specific management practices that will insure the best use of available energy and water for tree growth.

WRENSS: AN OPERATIONAL EXAMPLE

Hydrological models are usually not made for management purposes but rather for research purposes, or at best, for consultive management. Typical water-balance models require site-specific meteorological data supplied on a daily basis. Streamflow routing models require additional detailed information about soil properties and basin geomorphology. Models often require extensive calibration in order to validate parameters for specific regions. How then can hydrological modeling be used for day-to-day management of nonexperimental areas?

A good example of how to achieve such a goal is supplied by the WRENSS procedure. The remainder of this presentation will focus on the development and application of WRENSS for the prediction of water yield increases following harvesting.

The acronym WRENSS comes from the title of a handbook entitled *Water resources evaluation on non-point silvicultural sources* (United States Department of Agriculture, Forest Service 1980). The handbook was developed by USDA Forest Service hydrologists, and it assembled easy-to-follow procedures for predicting the magnitude of various effects of land use on water quantity, quality, and timing. In the more limited scope of this presentation, WRENSS refers to Chapter 3 of the handbook that deals with the estimation of seasonal ET. For the past few years, an ever-improving programmed version of this procedure has been offered by the Northern Forestry Centre's forest hydrology and microclimate project, with a few minor adaptations to our northern conditions. The latest version of the programmed WRENSS, for IBM PCs and compatibles, is available from the Centre.

The WRENSS procedure is a simple method for estimating ET of a parcel of land using a minimal number of inputs. It is not a model but the result of the application of models. It permits the estimation of seasonal ET for different regions, under different forest cover types, densities, and harvesting intensity and patterns. It makes possible the routine prediction of the effects of deforestation or afforestation on the average annual water yield of ungauged basins.

How Was WRENSS Developed?

The first step in the development of the WRENSS procedure was the division of the United States into seven forested areas of similar climate. These regions are shown in Figure 1 along with their possible Canadian extensions. Many experimental basins were then selected in each region, and one of two water-balance models was fitted to their streamflow and meteorological data. In the regions with major winter snowpack, the model used was WATBAL (Leaf

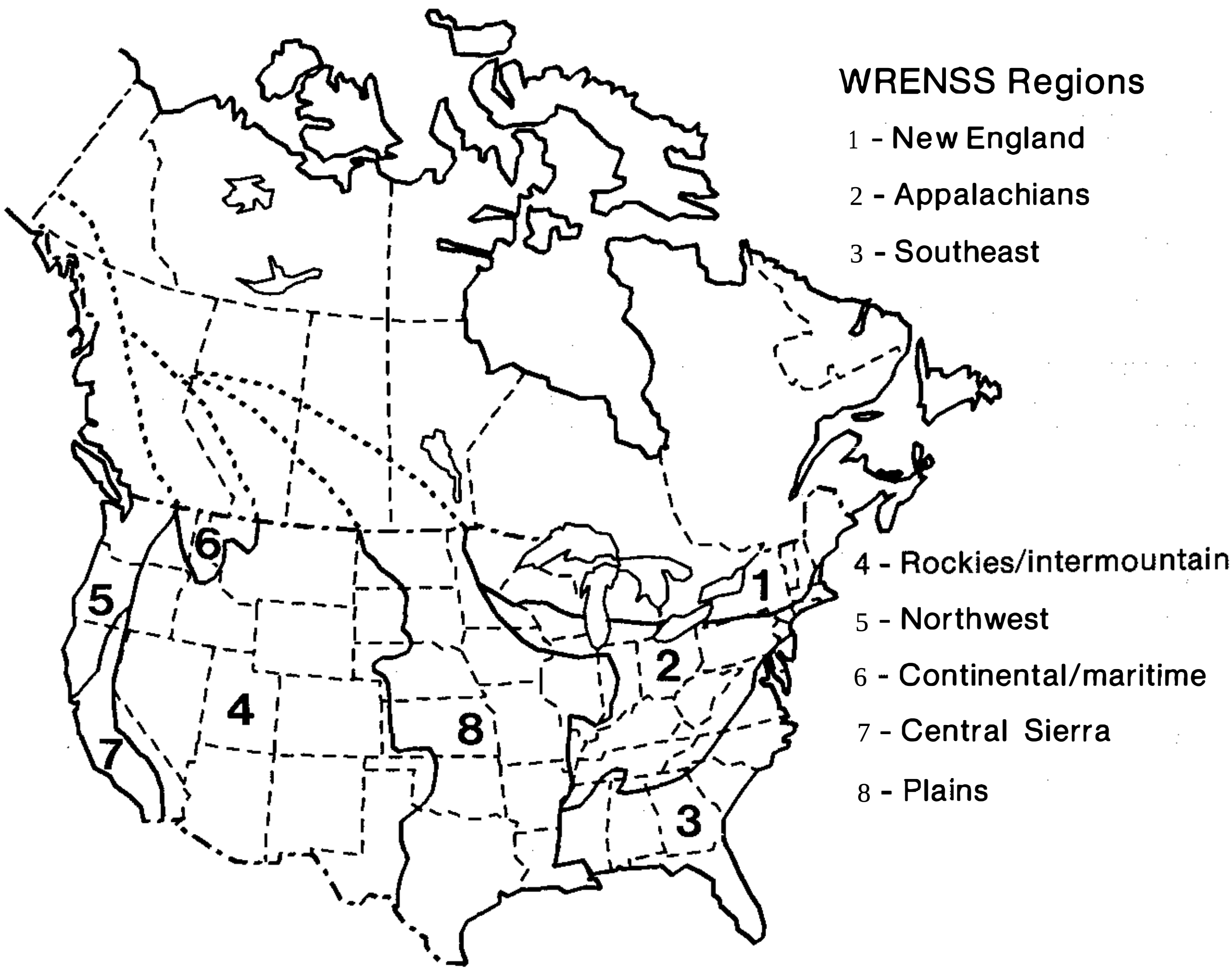

Figure I. Hydrological regions defined for the development and application of the WRENSS procedure in the United States, and their possible extension into Canada.

and Brink 1973b), a model that has a snowmelt simulator as its core. For regions where there was no snow or where snowmelt did not dominate the hydrological picture, the model used was PROSPER (Goldstein and Mankin 1972), a model centered on the mechanistic description of water movement in trees.

Simulations were first carried out on the baseline, or unaltered, condition of the experimental basins, using as many years of data as were available. Once this was done and the calibration was satisfactory, variables representing cover density, precipitation, and aspect of the basins were changed one at a time over a predetermined range, and the simulations were redone. Curves and coefficients relating ET to precipitation and to percent cover density were extracted by season, aspect, and region from all of these simulations. The resulting set of curves, the WRENSS procedure, is therefore an intricate table for simulation results, not a model. This distinction between procedure and model is very important because unlike models, WRENSS cannot be "calibrated" to a specific basin without going back to the original models themselves.

What Does WRENSS Require as Inputs?

Inputs for WRENSS can be divided into four groups. The first group, the geographical description of the land, includes the WRENSS region in which the basin is located, its area, and its aspect. The second group is the meteorological description of the unit. Precipitation is entered as totals per season. The WRENSS seasons do not correspond to calendar seasons but rather to portions of the year with similar hydrological behavior. Two other variables, length of winter in days and average wind speed, were added by us at the Northern Forestry Centre to better represent snow processes.

The third group is the stand description, with vegetation type, actual basal area, and maximum basal area of the stand expected at maturity. The fourth group, treatment description, requires the nonforested area of the unit, the average size of the openings, the height of the trees in the forested portions of the unit, and the average height (roughness) of debris and brush in the opening.

What Does WRENSS Give as Output?

The WRENSS procedure gives "seasonal" net precipitation and an estimation of ET for both the forested and nonforested portions of the basin, and, by difference, water yield. Because the WATBAL model is a water balance model only, WRENSS does not really compute streamflow but rather generated runoff (GRO), water that will sooner or later become streamflow but has not yet been routed through the ground.

The effect of forest cover modification can be computed from successive runs through the procedure. After computing GRO for an undisturbed basin, one can then compute the GRO of the same land area with various levels of afforestation or deforestation. The difference in GRO gives an estimate of treatment effect.

Example of Results

The following examples were produced by Robert Swanson of the Northern Forestry Centre as part of a series of lectures sponsored by the Canadian Water Resources Association. Figure 2 shows predicted against measured water yield increases following harvesting on four experimental basins (see Bates and Henry 1928, Troendle and Leaf 1981, and Swanson et al. 1986 for most of the original data). Percent cut ranged from 21% on Cabin Creek to 100% on Wagon Wheel Gap. Area of the cuts, an important parameter for the computation of snow evaporation, ranged from less than 1 ha for Fool Creek to about 80 ha for Wagon Wheel Gap. As can be seen, the effect of timber harvesting on water yield on the four basins was quite different. Both Fool Creek and Wagon Wheel Gap data were used in the development of WRENSS, so a good fit to the data from these two basins is not unexpected. Data from Cabin Creek and Streeter provide an independent test of the procedure.

CONCLUSION

These few examples of hydrological applications to forestry do not exhaust the field. One needs only to think of forest drainage, water logging following harvest, or even irrigation in nurseries to see other areas where hydrological knowledge is essential. Forestry is moving increasingly away from a forest harvesting-only operation toward more-integrated forest management. In such a context, hydrological knowledge, whether or not through modeling, will help managers make better decisions for both the water and the timber resource. In the area of estimation of water yield increases following harvesting, a model-based procedure is now available to forest managers. Models exist in other areas, but these are not suitable yet for easy and routine management application.

Finally, we should not think that water stress in trees is limited to low rainfall areas. Newly planted seedlings in clear-cuts can be subjected to debilitating water stress even during a short drought. Agriculture on the prairies has learned how to manage the vegetation to enhance water availability to the plant. Through hydrological studies and models, forestry can do the same and increase the survival and growth of seedlings and trees.

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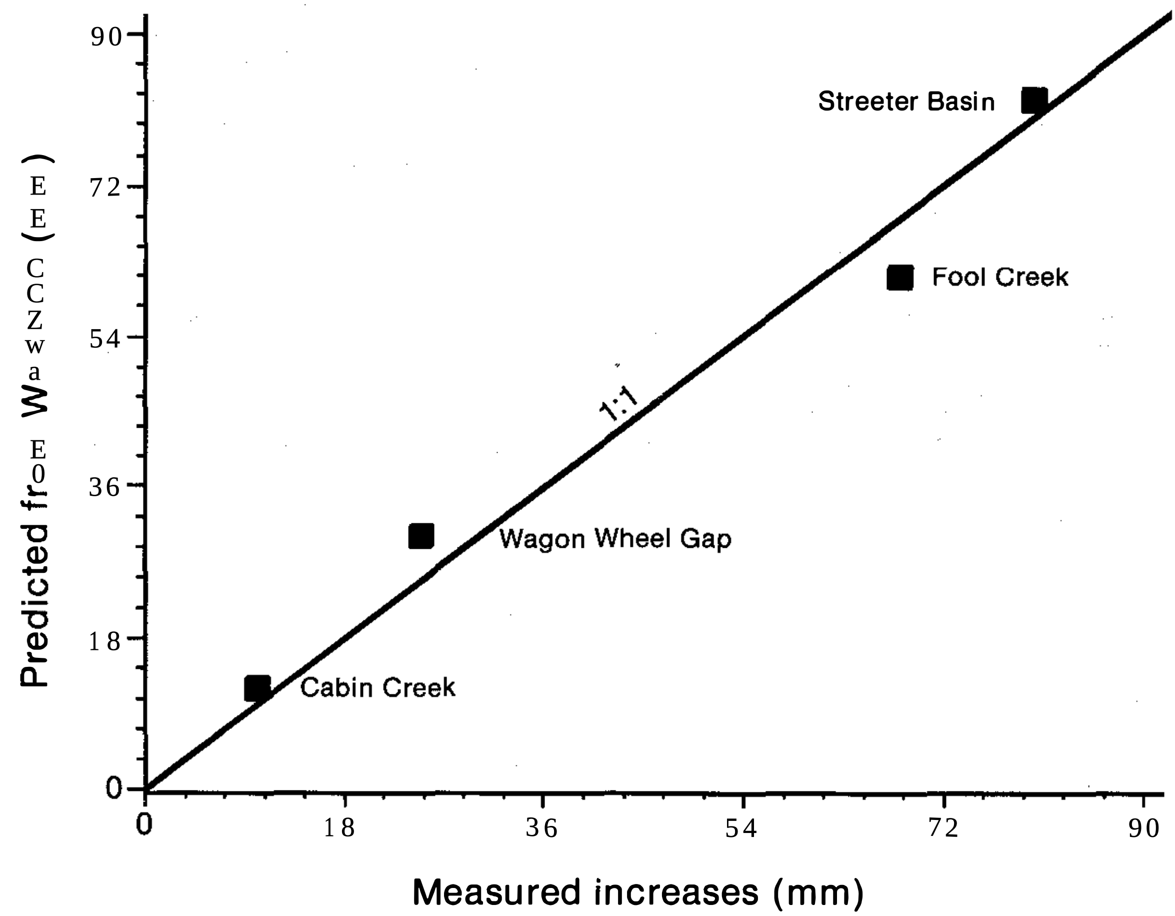

Figure 2. Predicted versus actual water yield increases following harvest on four experimental basins of west-central North America (analysis by R.H. Swanson).

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HABITAT MODELING IN THE WILDLIFE SECTOR

J.L. Kansas and R.M. Raine
Beak Associates Consulting Ltd.
Calgary, Alberta

INTRODUCTION

There is a trend in the forest industry toward the integration of multiple-resource themes into forest management planning. As a valuable consumptive and recreational resource that is directly linked to the land base, wildlife is becoming an increasingly important aspect of forestry planning. Timber managers deal regularly with numerical data that allow them to make objective decisions as to the timing and location of harvest. These data are often referenced to units of land in the form of mapped polygons. Wildlife biologists have historically lagged somewhat behind foresters in terms of their widespread acceptance and use of land-based assessments. In the past 10-15 years, however, the wildlife community has turned largely to habitat evaluations as opposed to direct population measurements.

Evaluating and integrating wildlife habitat into multiple land-use management situations can be a complex task. Habitat models are currently receiving widespread use as an objective and quantifiable tool for wildlife resource values for integrated land planning and management. This paper provides a brief overview of the principles and methods of habitat modeling in the wildlife sector. It also discusses how wildlife habitat modeling may best be used to include wildlife with forest management planning.

MODEL DEFINITIONS

To set the stage for this presentation it is probably most important to define what is often a highly misunderstood term, i.e., a model or modeling. Three useful definitions of what constitutes a model are as follows:

1. A simplified description of system to assist calculations and predictions (Concise Oxford Dictionary 1982).

2. A system of postulates, data and inferences presented as a mathematical description of an entity or state of affairs (Webster's New Collegiate Dictionary 1981).

3. A simplified representation of reality which presents significant features or relationships in a generalized form (Gelinas 1988).

As a wildlife biologist who deals regularly with insufficient budgets, my definition of a model differs somewhat from the above:

> A means of trying to indirectly represent real-world conditions, stemming from a realization that sampling budgets never seem large enough to tell the real story.

This tongue-in-cheek definition has some factual basis, as it is generally accepted that the complexities of wildlife interactions with their habitat will never be precisely mirrored (Thomas 1986; Salwasser 1986). Artificial models can, however, provide most managers with information of sufficient accuracy to meet their particular needs.

The preceding definitions pertain to modeling in its generic sense. Models of habitat or land-wildlife relationships are defined as follows:

> Land/wildlife relationship models are specifically designed to assess or predict the value of land features (habitat) and land areas to the maintenance and productivity of identified wildlife species. (Stelfox et al. 1989.)

The overall goal of habitat modeling is to assign a single value or rating to a unit of land for a particular season, species, or group of wildlife species. These ratings can then be used by wildlife managers on their own or in an integrated land-planning context.

WILDLIFE RESOURCE ASSESSMENT TECHNIQUES

To fully appreciate the true value of modeling it is necessary to discuss it in the context of wildlife resource assessments as a whole. There are three basic types of wildlife resource assessments, as follows:

1. Population status assessments
   - Current or projected population status
   - Critical or key area designations

2. Habitat status assessments
   - Current habitat suitability
   - Inherent habitat capability
   - Potential habitat capability

3. Multiple species occurrence (diversity) assessments

Because the topic of this presentation focuses on habitat modeling, I will avoid detailed discussion of population and diversity measurements. Suffice it to say that both population status and diversity assessments are also the subject of modeling studies and can be linked to habitat status assessments through carrying capacity measurement (Demarchi et al. 1983; Raedeke and Lehmkuhl 1986) and guilding or life-form procedures (Short 1984; Thomas 1979).

HABITAT STATUS ASSESSMENTS

Habitat assessments usually focus on easily measured physical and biological land attributes that contribute to or detract from the food, cover, and spatial requirements of a wildlife species. Other factors, such as land use (e.g., hunting pressure, cattle grazing intensity), competition, and predation levels, are usually not directly considered in these types of evaluations, even though such factors are often of indirect importance in assessing the availability of habitat requirements such as food and cover for security. These factors are very hard to measure and quantify. Climate data may or may not be an integral component of a habitat evaluation. It is therefore important to clearly define the scope, time frame, and intent of habitat assessments. The following terms and definitions are suggested for three broad, generic types of habitat assessments.

1. Current habitat suitability: This type of evaluation identifies the current ability of a land unit to provide a wildlife species with the environmental conditions needed for food, cover, and space. This assessment is current-time specific and would reflect existing vegetation cover (including successional stages) as influenced by natural and man-caused disturbance.

2. Inherent habitat capability: This identifies the natural or inherent ability of a land unit to provide a wildlife species with the environmental conditions needed for food, cover, and space. This assumes little or no interference by man, with natural vegetation cover being present and representative of relatively stable climax or disclimax type. The Canada Land Inventory (CLI) for ungulate capability and waterfowl capability represents this type of habitat assessment (Perret 1969).

3. Potential habitat capability: This identifies the potential ability of a land unit at some future point in time to provide a wildlife species with the environmental conditions needed for food, cover, and space. This assessment is based upon a knowledge of the range of potential future environmental conditions that may occur in a given area as a result of predictable man-induced or natural vegetation successional changes.

The three principal methods of rating a land unit's suitability or capability to support wildlife species are habitat use data collection, subjective manual assessments, and modeled assessment. All three techniques are subject to a number of shortcomings, especially if used as single-evaluation sources. When used in combination, however, they may serve as cross-checks and validators to one another to produce accurate land-unit ratings.

Habitat Use Data Collection

Field data collection in the context of most ELS has historically involved rapid and indirect habitat use measurement in the form of ungulate pellet group counts, snow tracking transects, breeding bird song transects, and small mammal trapping. The primary advantage of these types of field surveys is that they provide the inventory biologist with objective, study area-specific habitat-use measurements. Unfortunately, field assessment conducted over a short time-frame (less than one full year) may provide misleading or inadequate habitat-use information. One of the major problems associated with short-term field assessments is that they may not always reflect temporal nonhabitat factors such as hunting mortality, predation, traditional land use patterns, and indirect human harassment (e.g., intensive road traffic).

Subjective Manual Assessment

This method of evaluation uses the collective judgment of species experts to produce an overall, subjective rating for the land unit and species in question. The expert biologists use their local or regional knowledge of habitat use of the species along with biophysical information relative to the land unit to rate the unit's suitability or capability. The success of this type of assessment hinges on three main factors: the type and level of detail of biophysical information presented for land units; the amount of local or regional wildlife field experience of the expert biologists; and the amount of existing habitat-use research and inventory information present for the survey area or representative ecoregion.

Currently, the ability of plant and soil-landform ecologists to classify and map biophysical features exceeds the capability of wildlife biologists to subjectively assess their relative value, without the aid of field data. As the body of habitat-use research information grows, this disparity will lessen and the effectiveness of subjective assessments will improve.

Modeled Assessments

Detailed discussion of the methods of modeled habitat assessments is forthcoming in a paper. The pros and cons of modeling versus subjective and habitat-use field assessments will, however, be discussed here. The main strength of modeled habitat evaluations is that they are documented, repeatable, and quantifiable. The important advantage of models is that they make intuitive or invisible assumptions of the wildlife expert more visible and tangible. Subjective evaluations have the limitation of not being repeatable, of incorporating selective individual biases, and of not being available for scrutiny by others (Stelfox et al. 1989). Finally, model development by its interactive nature forces the biologist to refine and test aspects of wildlife interaction with habitat that are required to make an accurate assessment of habitat suitability or capability.

DEVELOPING A WILDLIFE HABITAT MODEL

A number of steps are required in the process of developing a land-wildlife relationship or habitat model. These five steps in model development are discussed below.

Setting Model Objectives and Desired Outputs

The first step in model development is to clarify model objectives and desired outputs. This includes choosing the type of assessment desired (e.g., suitability or capability); the number of habitat rating classes; the breakdown of ratings by season versus a single annual rating; the species of consideration; and the geographical area of consideration (most habitat models should be geared to a particular ecoregion).

Selecting Model Components

This step involves the selection of those habitat attributes thought to be most effective and practical for modeling habitat suitability or capability. This necessitates a thorough review of the habitat requirements for the species and geographic area under consideration. Habitat requirements should be documented in the context of life requisites such as food, cover, and space and divided into seasons of interest. Often it is necessary to choose those variables that can be readily identified and measured by remote sensing. The final choice of variables depends on the user's needs, scale of mapping, and level of management or planning.

Constructing and Operating Model

Once the seasons, life requisites, and habitat attributes (measurable variables) are selected they must be structured into quantifiable relationships that will yield an overall habitat evaluation. A tree or dendogram diagram as shown in Figure 1 may be used as a framework for structuring these relationships. A numerical rating must be chosen for each measurable variable. Figure 1 also outlines an example of calculated variable scores for a modeled evaluation of current habitat suitability.

Some of the important questions for consideration in defining the relationships between variables within a model include the following (Stelfox et al. 1989):

1. Should some variables carry more weight or importance than others?

2. Should low scores for some variables be limiting to the overall habitat suitability, or can they be compensated by other variables?

3. Should the size and proximity of adjacent vegetation cover types or land units influence the habitat suitability rating?

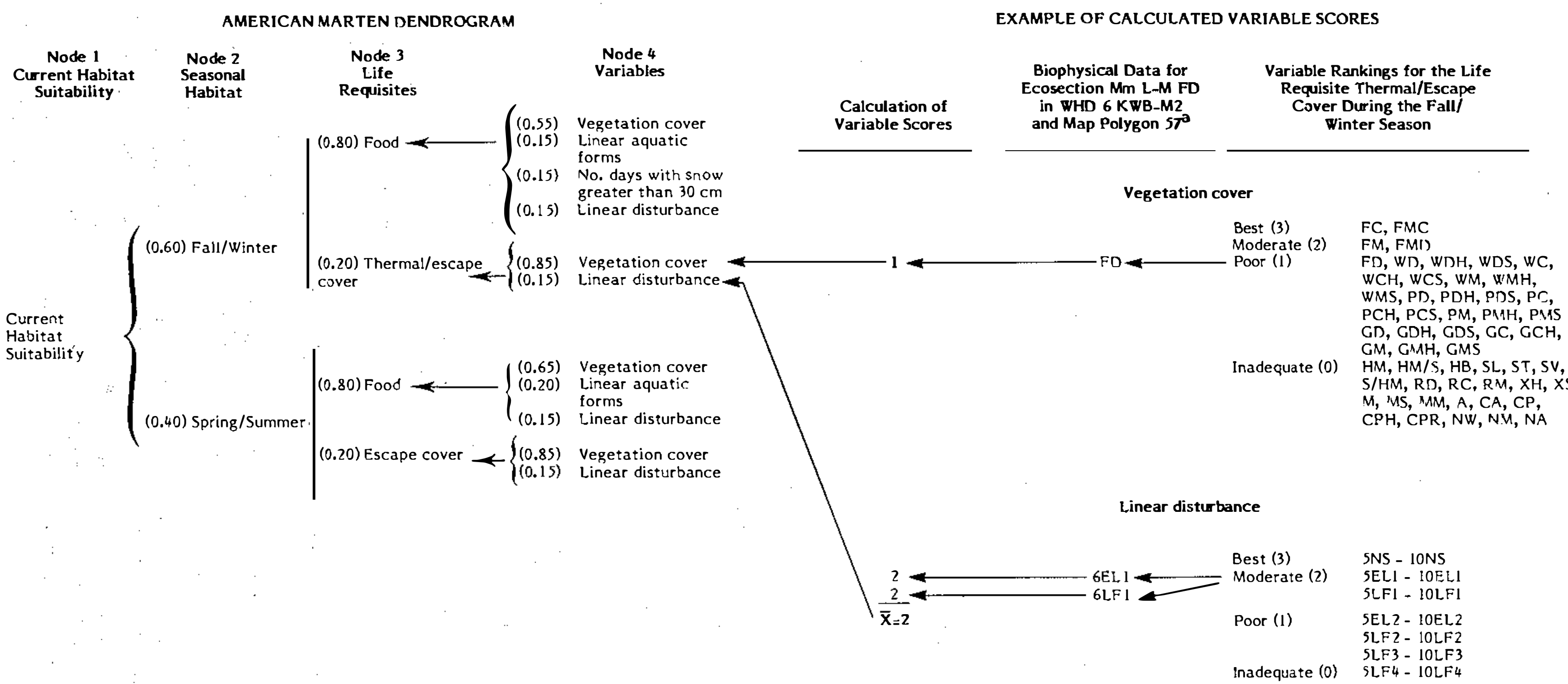

Figure 1. American marten dendogram (left) and an example of how variable scores are calculated, by ecosection (right). Aggregation weighting values on the dendogram are shown in brackets. A current habitat suitability value for a given ecosection is calculated by inputting a variable score (0-3) for each variable identified at Node 4 and calculating weighted averages in a stepwise fashion from Node 4 through Node 1. A current habitat suitability value is calculated by summing the ecosection values.

Such factors need to be dealt with in structuring relationships between model variables so that useful end products accrue.

The final habitat value for a particular unit is obtained through a calculation or formula that defines the functional relationship between variables.

Documenting the Model

To fully optimize their benefits, models must be thoroughly documented. This should include identification of the assumptions and rationale used, the scope and objectives of the model, and the inherent limitations of its applicability and accuracy. Thomas (1986) stated that "...people who produce and use models have the responsibility to explain processes, assumptions, strengths and weaknesses to those who make decisions based on these models."

Validating the Model

Because models are only approximations of reality, their end products should be tested or validated in some way. Modeled habitat ratings may be tested by expert-based subjective assessments and by field data. Testing should attempt to reflect the original assumptions of the model. For example, it may be inappropriate to collect and analyze habitat-use data as a test of habitat quality (Van Horne 1983). Researchers usually test the overall output of a wildlife habitat model; however, it is often as useful to test assumptions and variable values in order to improve model reliability (Schamberger and O'Neil 1986). This observation relates to the two principal uses of model testing: 1) to provide information about model performance and reliability in specific applications; and 2) to provide data that can lead to model improvement for both the model tested and for similar models.

EXAMPLES OF WILDLIFE HABITAT MODELS

In Saskatoon I presented an example of a habitat model that was used in support of black bear research in Banff National Park. For the sake of brevity, I have omitted this aspect of the presentation from this paper. Readers may contact the author to obtain copies of the modeling methodology used (Kansas et al. 1989). Readers are also directed to a recent overview of terrestrial wildlife habitat modeling by Verner et al. (1986).

IMPLICATIONS OF HABITAT MODELING FOR FORESTRY

In this section I would like to present some observations and concepts for applying wildlife habitat modeling to forestry. This discussion attempts to take into account two important facts:

1. that data availability is the key factor that limits or promotes the integration of wildlife resource values into forestry planning; and

2. that the availability type and accuracy of wildlife data varies widely between forest management or timber supply areas and political jurisdictions.

Input Data Availability

The type of wildlife habitat model used in a particular forest management setting will depend largely on the amount, type, scale, and style of mapped biophysical information available to the forester. Some examples of the types and range of mapped biophysical information available to forest managers are as follows:

- Ecological land classification (closed or open legend)
- Biogeoclimatic mapping
- Ungulate capability mapping
- Canada Land Inventory
- Vegetation classification
- Soil mapping
- Physical land classification
- Wildlife key area maps (e.g., winter deer yards)

All timber management areas of course have large-scale timber inventory maps to support harvesting. Increasingly, mapped biophysical and timber inventory data are becoming available in digital form, including in some cases digital topographic base mapping with digital elevation models. Availability of digital mapping is currently limited and dependent largely on the province in question.

Biophysical products vary widely in scale of mapping. Unfortunately, most maps are of a level of detail that provides information too general to be of use for harvest planning. Most wildlife species utilize habitat in a manner that is most appropriately "packaged" at a plant association level of detail. The 1:15 000-scale detailed timber inventory mapping used by foresters is a suitable scale to meet this requirement; however, understory conditions usually are not represented in the timber classifications.

The particular style of biophysical classification and mapping and the availability of multiple resource themes will influence the type of modeling used. If different themes of information are available (e.g., vegetation, soils, slope/aspect) in digital form, the modeling overlay capabilities of a geographical information system (GIS) should be considered. If, however, biophysical information is available in the form of an integrated land unit, then mathematical models need to be developed that produce habitat ratings on a polygon-by-polygon basis. In most instances, however, integrated land classifications are available at scale of mapping of 1:50 000 or less detailed. This level of information is difficult to work with in terms of detailed harvest planning and is often considered to be of little direct benefit to foresters concerned with integrating wildlife into their planning activities.

POTENTIAL SOLUTIONS

Two sources of land information that are available to all forest managers are detailed timber inventory and satellite imagery. These two sources may not be useful for wildlife purposes on their own, but when combined with appropriate fieldwork and other resource themes in a GIS environment may provide useful wildlife habitat interpretations. One potential means of providing foresters with a widespread source of mapped information with which to model wildlife habitat is to establish a link between understory conditions and detailed timber inventory polygons. This would require pilot site classification projects within ecoregions to determine relationships between plant associations and terrain features. This is an ideal application of GIS as a support tool, especially if digital elevation information is available.

Once these vegetation-terrain relationships are understood, a link to detailed timber inventory polygons or grouping of polygons must be investigated. For example, it may be found that timber polygons with 80-year-old aspen of a given crown density that occur on flat, fluvial terrain tend to produce an aspen-red osier dogwood plant association. The wildlife biologist can then rate a particular land area based on existing knowledge of wildlife response to the plant association or complex of plant associations. It is well known, for example, that red osier dogwood is a preferred winter food or moose, and this strongly influences the winter importance of the aspen-red osier dogwood plant association.

Another alternative is to develop a model that rates each of a variety of habitat attributes (forest cover type, slope, aspect, landform, etc.) for particular life requisites that are used to calculate an overall value for land areas. This can be done as a modeling overlay in a GIS. This latter alternative requires considerable subjective assessment in the weighting of the relative importance of different habitat attributes to a species. Hence, final interpretations of wildlife habitat importance may not be as accurate as actually determining plant association occurrence and rating the plant association. It is always easier for a biologist to rate habitat types that include information on floristics, as wildlife usually "are where they eat" (and they generally do not eat landforms and soil).

Although not yet a proven technology for recognizing and mapping plant associations, there is potential to use satellite imagery, in conjunction with other resource themes in a GIS, to extrapolate pilot site classification mapping to a larger area (within the same ecoregion). Research is needed that provides a link between plant associations, large-scale timber inventory maps, and satellite imagery such that wildlife values can be integrated with forestry planning on an operational rather than pilot setting.

SUMMARY

Contemporary forest managers face an increasing demand to include a range of resource themes into timber management. Wildlife resource values are best integrated into forestry using a habitat rather than a population approach. Modeling provides a means of evaluating wildlife habitat in an objective and repeatable manner. This presentation reviewed habitat modeling procedures in a conceptual sense and offered some potential applications to the forest manager. It is hoped that these comments will stimulate further thought and discussion and will encourage future initiatives in the field of wildlife-forestry integration.

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IMPROVING FOREST MANAGEMENT IN NEW BRUNSWICK: THE USE OF TECHNOLOGICAL TOOLS

T. Erdle
New Brunswick Department of Natural Resources and Energy Fredericton, New Brunswick

INTRODUCTION

Remote sensing, modeling, geographic information systems (GISs), and image analysis are trendy topics in the forestry sector today. Each of these flashy high-tech tools has been the subject of numerous conferences, and from all the attention awarded them one might conclude that these tools are ends in themselves, rather than means to the end of improved forest management practices. In an attempt to clearly distinguish between means and ends, this paper will focus on forest management problems and the importance of solving them to improve management of the resource. Technological tools will only be introduced in terms of their contribution to problem solution. The objective here is not add to the literature on the technologies themselves but to indicate the way in which judicious use of technology can improve management. To realize this objective, this paper will address an applied cooperative research effort that is aimed at resolving a key operational problem in timber management planning in New Brunswick.

The left hand side of Figure 1 presents a general process by which technological tools can become solutions to operational problems. The discussion here will follow that framework, and the specifics for this case are listed in Figure 1 on the right. As shown, discussion will begin with a clear description of the problem at hand. It is important to clarify the problem, because its nature defines what constitutes a potential solution, and because a clear problem statement provides an unambiguous basis for evaluating the extent to which technology helps to solve the problem. The problem in this case is that of forecasting short-term volume development of mature spruce-fir stands in New Brunswick.

Next, discussion will turn to potential solutions offered by developing technologies. The potential solution in this case uses thematic mapper (TM) satellite imagery as input to a GIS forestry data base for use in stand growth forecasting models. Transformation from the potential to the actual solution requires considerable research and development efforts, each of which is discussed in turn. Research for this problem involves the development of reliable relationships between the spectral reflectance of spruce-fir stands and their canopy condition and current annual volume increment. Development activities include the operational integration of remote sensing data (TM imagery) and a GIS-based forest inventory for a 7 million-ha land base.

Once the necessary research and development is accomplished, there must be a context within which the technological solution will be brought to bear on the actual forest management problem. The context discussed here is the legislated 5-year management planning cycle under which New Brunswick Crown land licensees identify timber management strategies for implementation in ensuing years.

In discussing this effort to use technological tools in support of forest management, several important messages will emerge. These will be summarized in conclusion.

THE TIMBER MANAGEMENT PROBLEM: STAND GROWTH FORECASTING

Stand growth forecasting is probably the most fundamental component of timber management planning. Although it is an extremely complex topic, growth forecasting can be viewed as playing two simple but critical roles in timber management. First, it is the basis for the design of harvest schedules, which specify the rate and sequence by which stands will be harvested to meet a set of timber supply goals. Secondly, it is the basis for designing silviculture and protection activities, which are meant to control stand growth and guide it toward some desired end. The effectiveness of harvest scheduling, silviculture, and protection activities in meeting wood supply goals is a direct function of the quality of stand yield forecasts upon which they are founded.

Figures 2 and 3 illustrate the matter in very simple terms. In Figure 2, the harvest schedule prob-

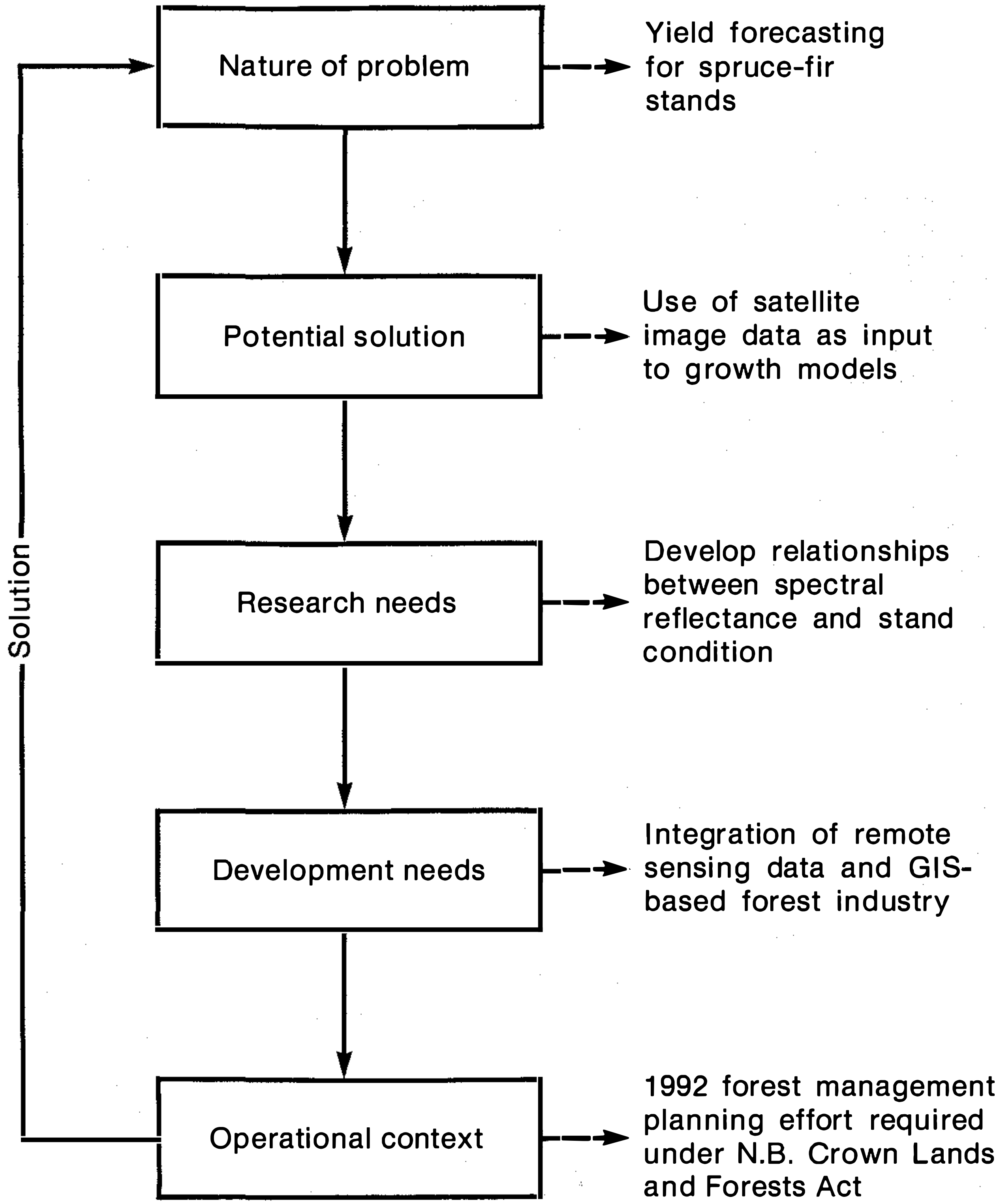


Figure 1. General framework for implementing technology to solve forest management problems. Specific counterparts for the New Brunswick project are shown at right.

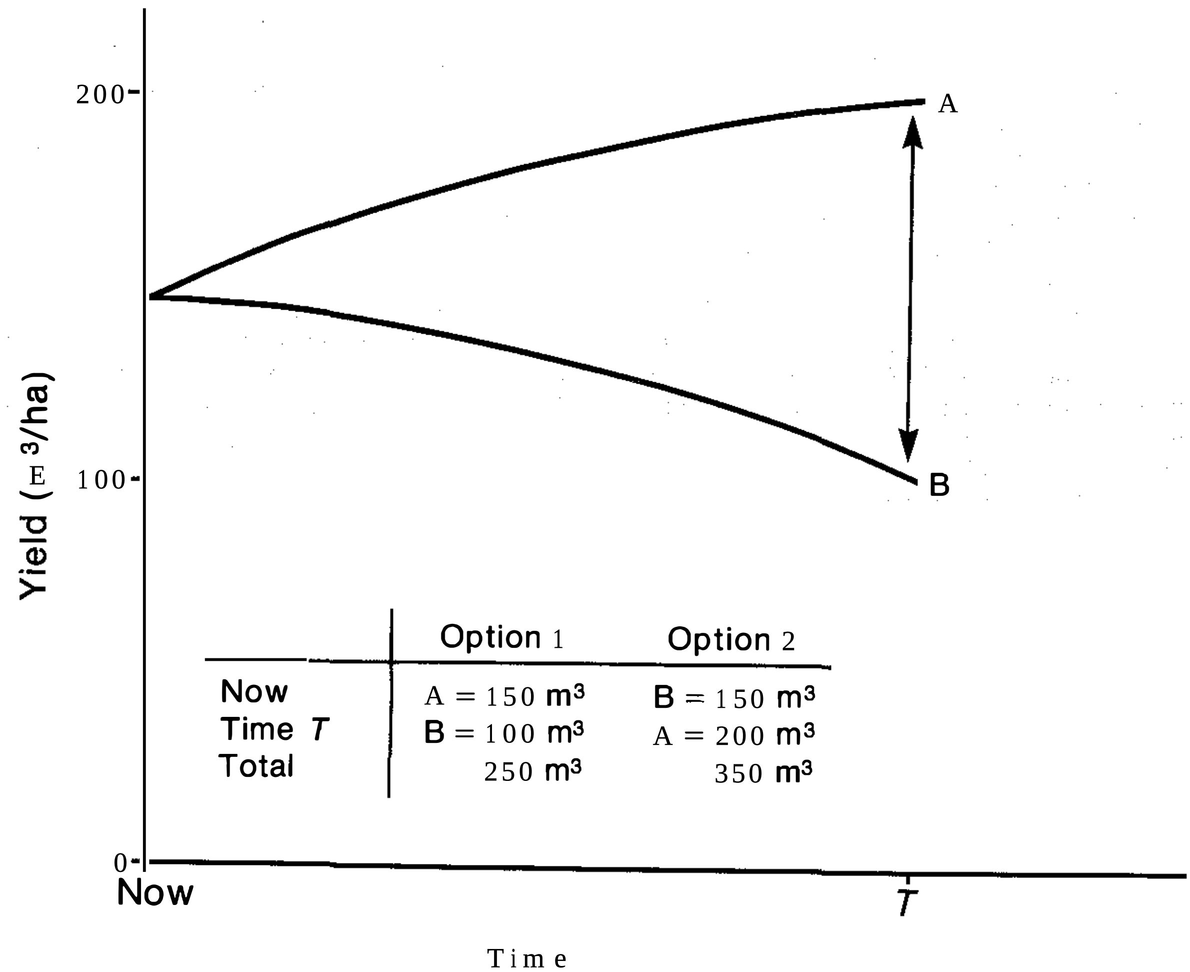


Figure 2. The role of yield forecasts and effect of harvest scheduling on wood supply.

lem is simply posed for two stands, whose yield between now and time T is predicted as shown by the curves. One stand is to be cut now and one at time T. What is the best schedule? Of the two choices (Stand A then B, or B then A) the second is clearly superior because it harvests tbe declining Stand B now and defers the harvest of Stand A, which shows volume accrual to time T. The total harvest (350 m^3) under the second option is 40% higher than tbat available under the first (250 m^3). This is a very simple case, but it contains two very important messages. First, it reveals the value of information, particularly the value of reliable stand yield forecasts. No conventional management activities were performed; no trees were planted, no insects killed, no fires put out. Solely by having and using the yield forecasts to design the sequence in which stands would be cut, the forest productivity was increased substantially. In the absence of discriminating yield forecasts, stands A and B would be indistinguishable from a yield standpoint, and the opportunity to choose tbe most productive sequence would vanish. From tbis perspective, the case to fund information acquisition is every bit as compelling as the case to fund silviculture; accurate information properly used can increase wood supply just as silviculture properly executed can. The second point is tbat the difference in yield between stands must be anticipated at the start of the planning period. It is of little value to observe or measure differences in behavior as they occur because by that time it is too late to respond to the findings. The harvest choices will have already been made.

Figure 3 extends the simple two-stand example to the design of interventions. In this case, stand yield forecasts are necessary to signal unanticipated changes in stand development to allow steps that will prevent the change or to allow response by reordering the harvest schedule. In Figure 3, the B-then-Aharvest sequence is selected for implementation, and the expected outcome is a total harvest of 350 m^3. In actuality, Stand A is damaged in some way and its real yield is shown by A' rather than A. With no response to the change, Stand A would be harvested at time T and would produce only 75 m^3 rather than 150 m^3. Obviously, wood supply expectations and reality do not match, with unattractive consequences. Yield forecasting here would have signaled that A's performance was not as expected, and anticipation of the A' yield behavior would allow taking steps to mitigate the impact. The specific situation would dictate the action, but here the choices are to protect Stand A to prevent the A' yield or reorder the harvest and cut Stand A now and Stand B later.

Although the two simple cases are useful to illustrate the role and importance of yield forecasting, it is important to indicate the significance of the problem from an operational standpoint. A 1000-plot permanent sample plot (PSP) network in New Brunswick serves to illustrate. One thousand PSPs in spruce-fir stands in New Brunswick were measured in 1980 and remeasured in 1983. Each plot can be represented by a point in an X-Y plane, where the X value equals the 1980 m^3/ha and the Y represents the 1983 m^3/ha (Fig. 4). Drawing a 45° line through the plane serves as a reference by which to evaluate the periodic annual stand increment for the 3-year period. Three stands, one each of no volume change, positive volume change, and negative volume change are represented in this fashion in Figure 4. Figure 5 represents the full set of 1000 plots in the same format.

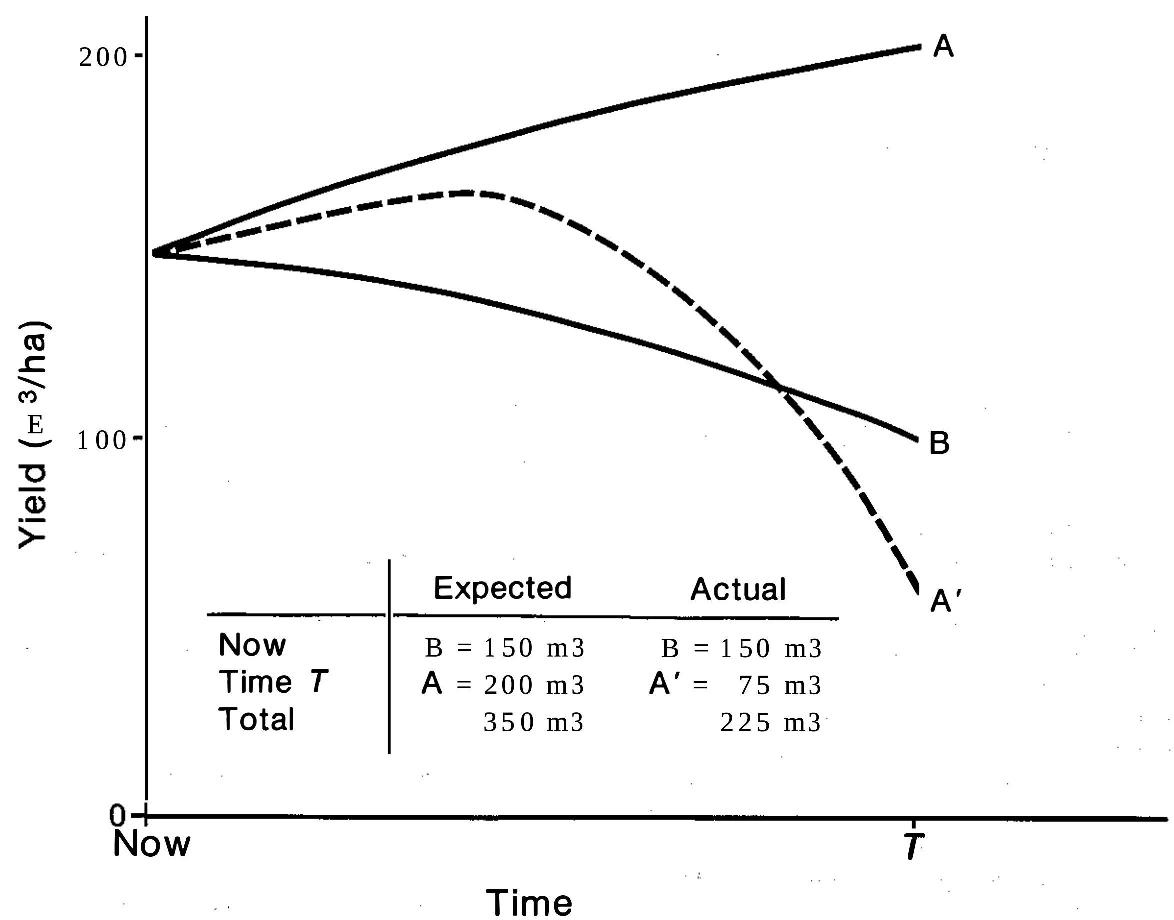


Figure 3. The importance of yield forecasts in designing interventions.

Stand	1980 volume (m^3/ha)	1984 volume (m^3/ha)	Net change
1	75	75	0
2	100	110	+10
3	100	80	-20

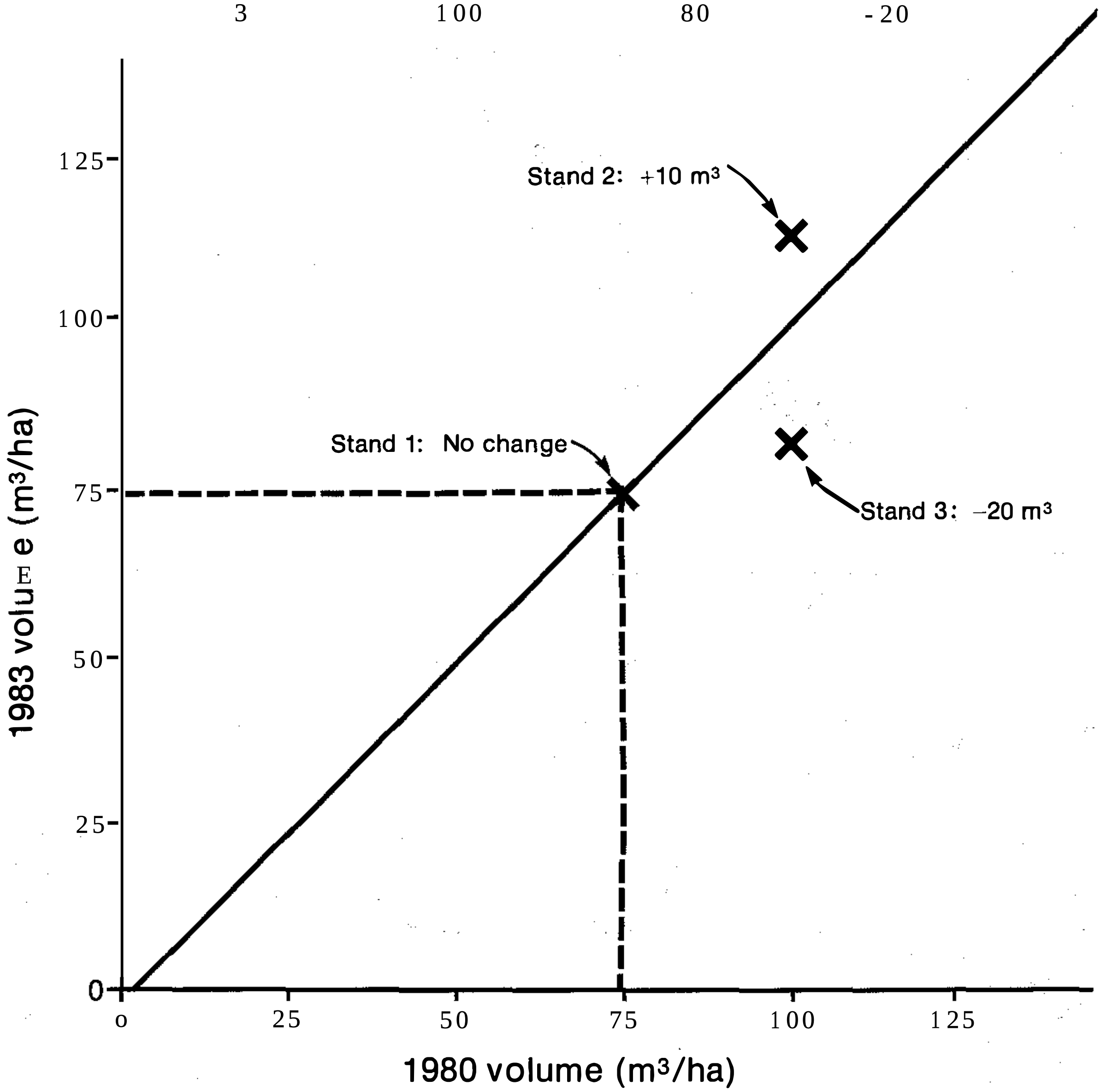


Figure 4. Format for displaying periodic annual volume increment for permanent sample plots.

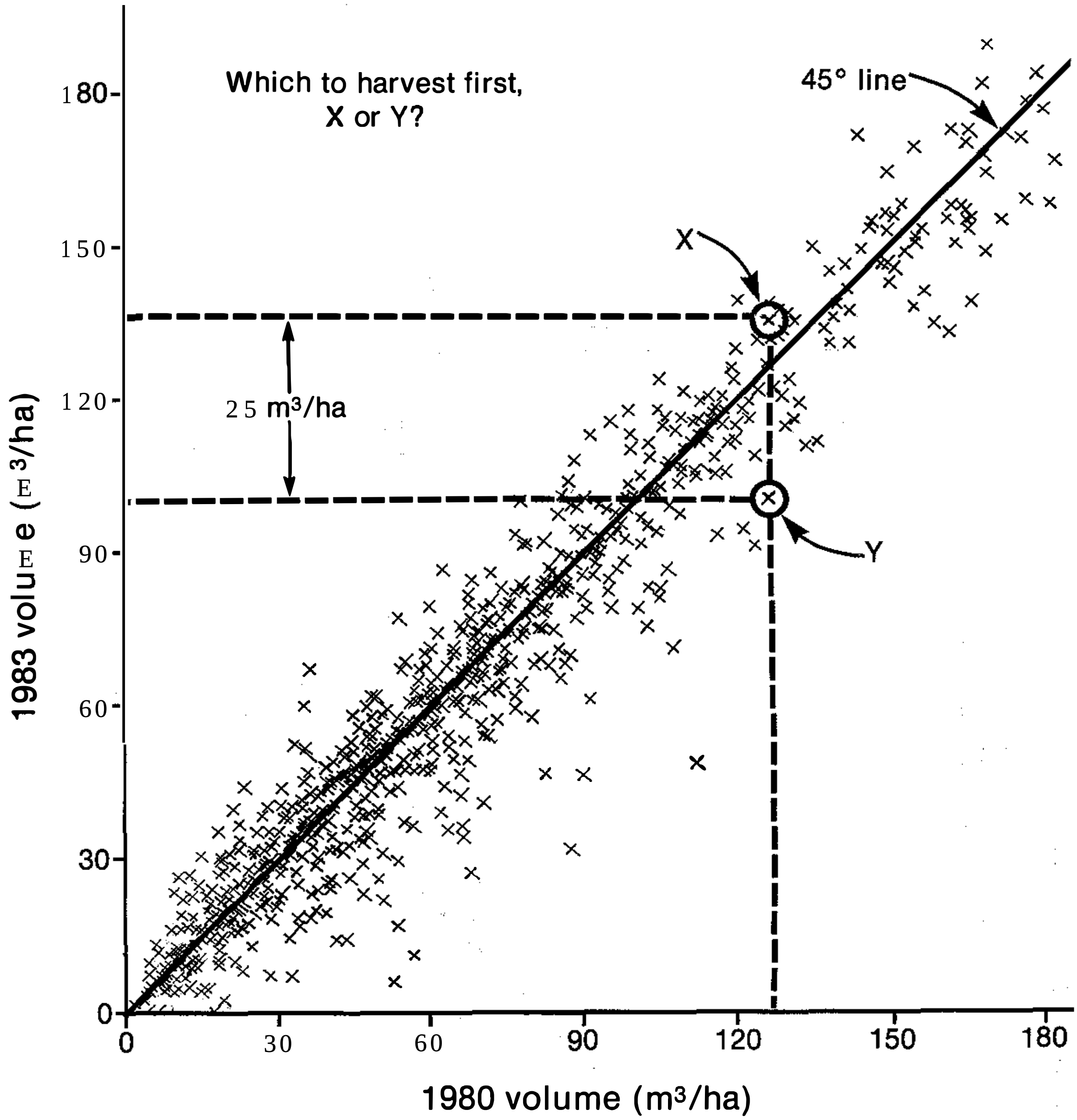


Figure 5. Live spruce and fir volume in 1980 and 1983 for 1000 PSPs in New Brunswick. Departure from 45° line indicates periodic volume increment.

Two features of the scatter of points are particularly noteworthy. First, many stands reside below the 45° line. This reflects the abundance of deteriorating mature and overmature spruce-fir stands in New Brunswick. Their abundance poses an obvious and important harvest scheduling problem. The second feature of note is the high degree of variability in 1983 volumes between stands of similar 1980 volumes. Interestingly, most forest inventories characterize stands in a way that distinguishes between stands of different absolute volumes, which is of little help here where the problem is to distinguish between stands with different rates of volume change. Thus, an alternative to conventional inventory procedure is required.

The variation in volume change between stands shown in Figure 5 signifies frequent actual occurrence of the simple hypothetical cases present in Figure 2. In the real forest the same scheduling questions exist as for the simple case, as do the same scheduling implications to wood supply, and as do the same needs for accurate yield forecasts. The only difference between the real and simple case is the size of the stakes. The difference in volume change for stands X and Y in Figure 5 is 25 m^3/ha. If each stand is 40 ha, the harvest timing choice between the two stands represents a potential harvest increase or decrease of 1000 m^3. Given the number of harvest choices made annually and the complexity and diversity of the forest as shown by Figure 5, there exists considerable opportunity to enhance wood supply with the right decisions or to erode them with the wrong ones. Unlike errors common in forest inventory, errors in harvest timing are noncompensating. All timing errors have one way effects in that right decisions never offset wrong ones.

Figure 5 is a graphic illustration of the operational significance of the stand yield forecasting problem to wood supply. It clearly reveals the value of information that can improve yield forecasts, and it also shows the value of sound yield forecasts in making effective operational timber management decisions. It further makes a compelling case for earnest pursuit of solutions, technologically based or otherwise, that can contribute to improved yield forecasting.

THE POTENTIAL SOLUTION

Around 1984, when some of the implications of the Figure 5 data set were being interpreted, new satellite imagery became available from the thematic mapper (TM) sensor on LANDSAT IV. As part of a productive and continuing working relationship between the New Brunswick Department of Natural Resources (NBDNR) and the Canadian Centre for Remote Sensing (CCRS), Dr. Frank Ahern of the latter agency came to the province with samples of the TM imagery. Several field visits with NBDNR, Fraser Incorporated, and CCRS staff revealed many useful interpretations of the new imagery. One of particular interest was an apparent correlation between stand canopy condition as observed on the ground and reflectance values as evidenced in the imagery. Given this apparent correlation and the compelling need for discriminating short-term yield forecasts just discussed, it seemed worthwhile to pursue the development of reflectance versus stand condition (evidenced by volume increment) correlations more thoroughly and systematically.

A low-budget cooperative study was undertaken by CCRS, NBDNR, and Forestry Canada to determine if such correlations might be sufficiently strong to be a useful complement to stand growth forecasting. Ahern et al. (1989) report the study in detail. Key aspects are summarized here. The study used existing permanent sample plots as the sample units and their measured volume increment as the dependent variable in the correlation. The plot locations were fixed on the imagery, and the pixel reflectance values in the seven TM spectral bands made up the corresponding independent variables. Statistical analysis of various independent variable combinations were made; the most promising result is presented in Figure 6 (from Ahern et al. 1989). The figure shows reasonable correlation between VC15 (which is TM band ratio 7/4) as extracted from the TM imagery and periodic annual volume increment as measured in the plots.

The result is exciting because the predicted Y variable is precisely what is needed to design productive harvest queues for conditions illustrated in Figure 5. Further, the predictor X variable is available relatively cheaply and on a forest-wide basis. It is possible that adding other independent variables to the regression (e.g., species composition and crown closure) could strengthen the results, yielding a final statistical model of the form:

$$\text{Volume } [(m^3/ha)/yr] = f(\text{VC15, species composition, crown closure}).$$

Data to drive this model would come from two sources: VC15 from TM imagery and species and crown closure variables from the forest inventory.

FURTHER RESEARCH

Although the correlations between reflectance and stand condition correlations looked promising, the initial study suffered a number of shortcomings that precluded operational use of the results. These included 1) a small sample size (78 plots aggregated into 9 groups); 2) evaluation of plot-level, not stand-level, behavior; 3) limited geographic coverage; 4) no accounting for species variation; 5) failure to address between-scene and between-date TM variation.

In recognition of these shortcomings, while hoping to capitalize on the promising initial results, a more comprehensive and rigorous study was funded and undertaken in the spring of 1988. The effort involves the cooperation of Forestry Canada, New

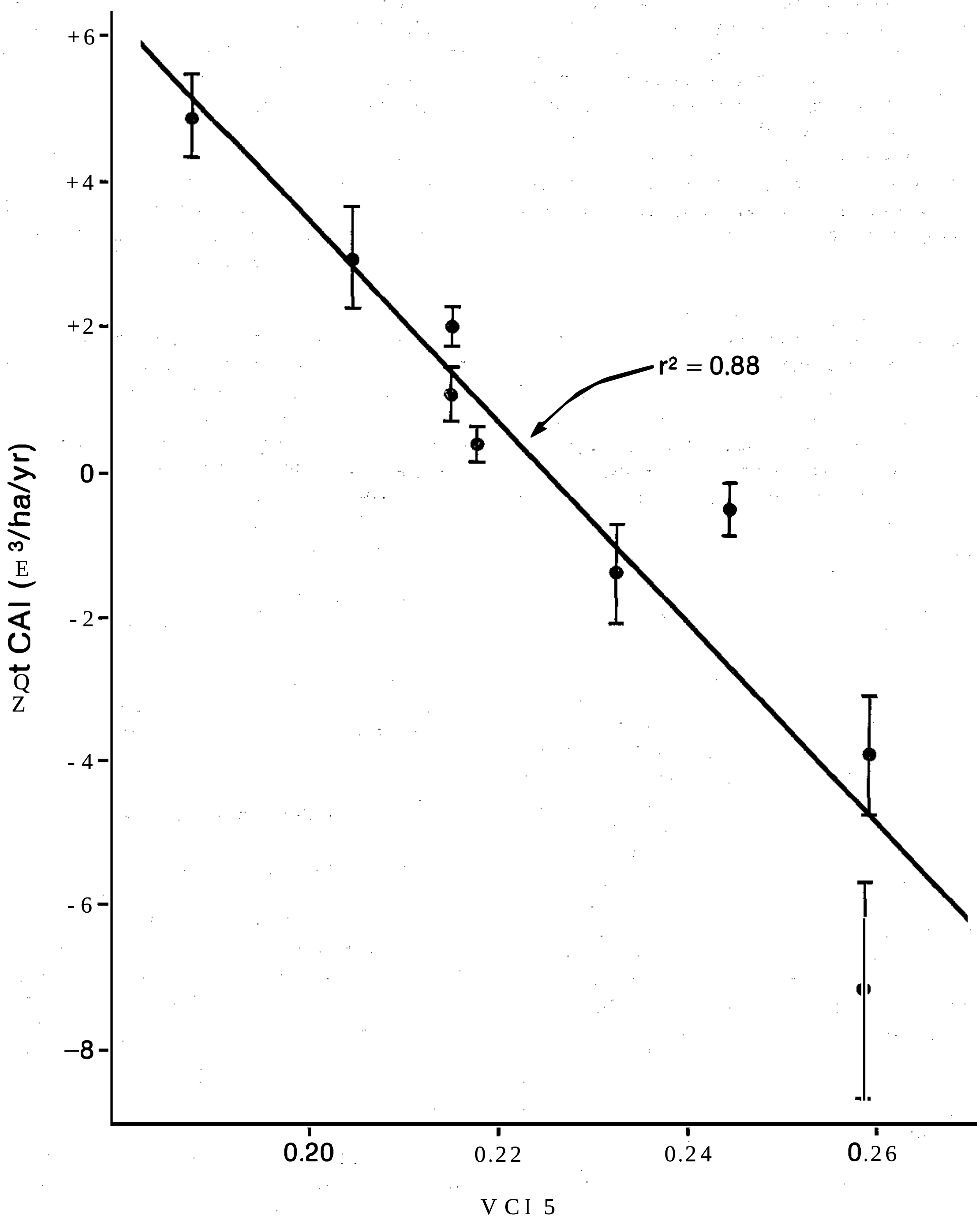


Figure 6. Relationship between current annual increment and VC15. VC15 is TM band ratio 7/4 (from Ahern et al. 1989).

Brunswick Department of Natural Resources, Canadian Centre for Remote Sensing, New Brunswick Forest Research Advisory Committee, and Université de Moncton at Edmundston.

The new study will be ongoing until the spring of 1990 and is aimed at establishing the types of relationships shown in Figure 6 for volume increment and for variables of canopy condition (defoliation). The current study redresses the shortcomings of its predecessor by 1) expanding sampling to the stand level, which is more meaningful operationally and more consistent with TM resolution; 2) making more detailed observations of stand canopy characteristics; 3) sampling across a range of species mixtures; 4) sampling to provide geographic coverage of the entire province; and 5) sampling across many TM scenes to address the issue of between-scene radiometric standardization.

There are a number of technical issues that must be resolved in construction of the relationships, and there is no guarantee the results will be sufficiently strong for operational use. The potential payoff more than justifies the investment in the study, however, and the scientific expertise of the cooperating agencies maximizes the likelihood of success.

DEVELOPMENTAL REQUIREMENTS

Assuming the current research establishes reliable relationships between stand condition and spectral reflectance, there remains development work to create the mechanism through which those relationships will be used to make stand-specific yield forecasts necessary for operational harvest schedule design. For operational use, the predictions of volume increment must be available on a stand-specific basis and comprehensively across all the harvest candidates. In New Brunswick the digitally mapped, stand-based forest inventory is the only comprehensive data base with stand level resolution; consequently, use of the stand-condition correlations is only possible through integration of the GIS-based inventory and the TM imagery.

The developmental work necessary to integrate the two data sets has only recently begun. The conceptual design is shown in Figure 7. The approach starts with the New Brunswick GIS forest inventory (structured and maintained on an ESRI ARC/INFO system), complete with digitally mapped stand boundaries and associated photo-interpreted attributes of species composition, crown closure, and maturity. Thematic mapper scenes are then registered to the geo-referenced inventory, and the TM pixels are assigned to the appropriate stands in the GIS base. The spectral values that make up the independent variable in Figure 6 are then computed for each stand based on the reflectance of its resident pixels. The final step is to solve for the dependent variable (volume increment) using the appropriate equations and to insert the predicted increment value into the stand attribute records in the GIS data base. Successful development of the process would provide a tremendous opportunity to capture the wood supply benefits available from judicious harvest scheduling.

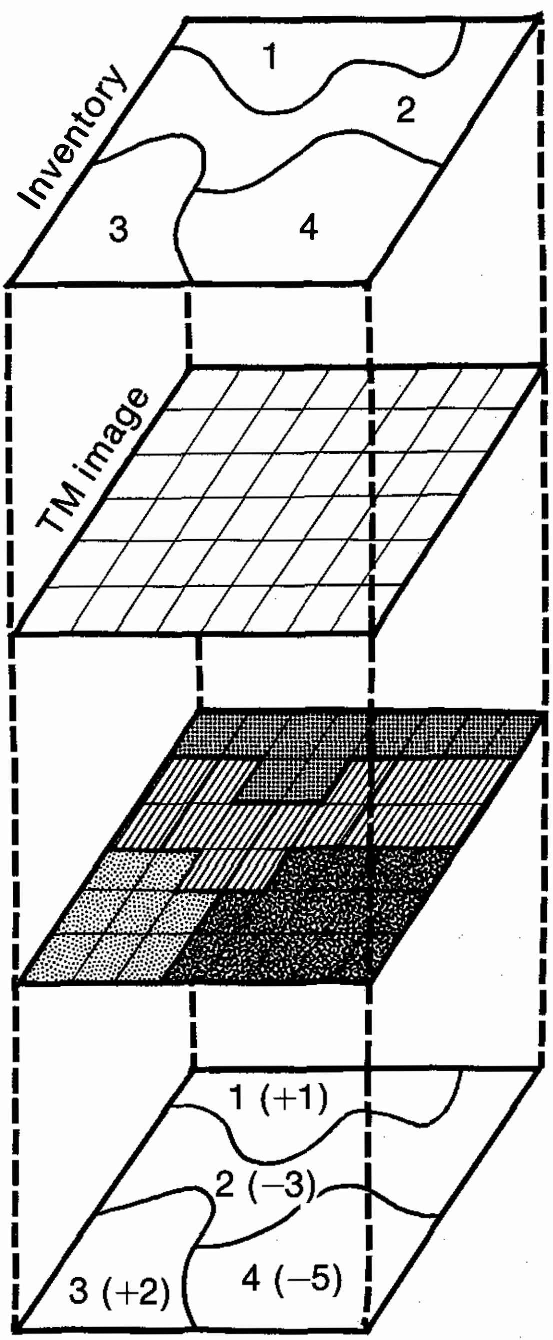
OPERATIONAL IMPLEMENTATION

How exactly would the opportunity be captured? Under the New Brunswick Crown Lands and Forests Act, spatially explicit management plans must be prepared for Crown licenses at 5-year intervals. These plans include silviculture regimes and mapped harvest schedules that are efficient in sustaining a high harvest level for the license. The next series of plans will be submitted in 1992.

The intention is to have all the research and developmental work accomplished so that stand attributes can be appended with forecasts of volume increment by 1991. This information would then be available directly for use in the management planning process required for 1992 (Fig. 8). Assuming that all the described lead-up tasks are successfully executed, the 1992 management planning task represents a sharply defined end-point to close the "problem-technology-solution" loop necessary for meaningful improvement in stand yield forecasting capabilities.

SUMMARY

The effort described here is attempting to capture the advantages of high-technology tools of remote sensing and GIS and focus them on the solution of the fundamental forestry problem of stand yield forecasting. Although the financial, scientific, and management committee to the project bodes well, there is no guarantee of success. Regardless of the outcome, this effort illustrates a number of noteworthy points.



Stand	Photo attributes
1	bF 10 I 5
2	SP 10 M 4
3	bF 10 M 2
4	SP 10 M 3

Coregister and link GIS data base and satellite image

Calculate reflectance and solve for increment

Stand	Photo attributes	△ volume
1	bF 10 I 5	+1 m^3/ha
2	SP 10 M 4	−3 m^3/ha
3	bF 10 M 2	+2 m^3/ha
4	SP 10 M 3	−5 m^3/ha

Figure 7. Conceptual design for integrating TM imagery and GIS forestry data base. Result of process is volume increment appended to each stand's descriptive record.

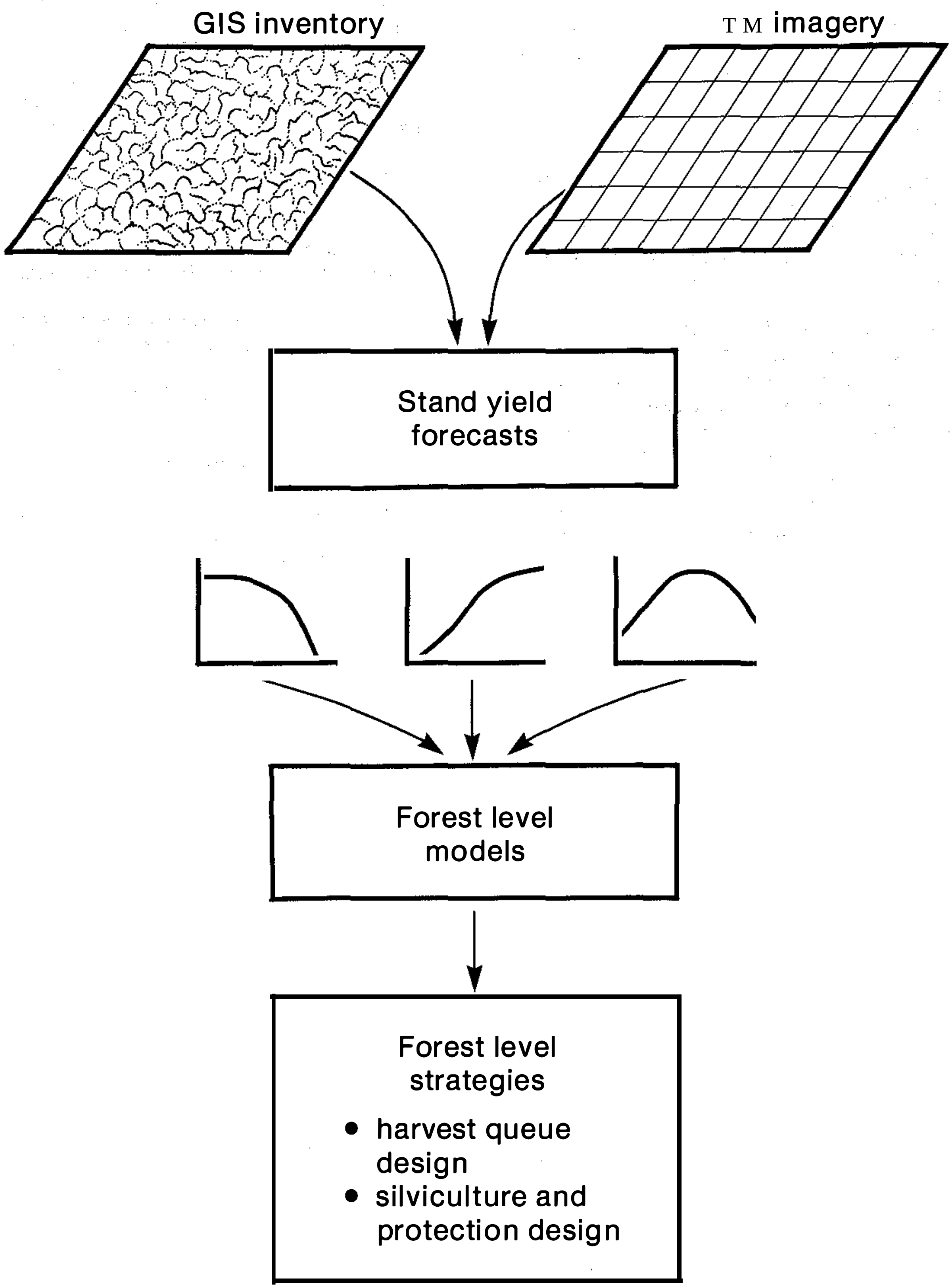


Figure 8. Conceptual framework for incorporating yield forecasts in 1992 forest management strategies.

1. The problem demonstrates the value of forest resource information in tangible units—here, cubic metres of wood supply. This demonstration is important to maintain financial support of forest information programs, which sometimes are early victims of budgetary limitations.

2. The problem reveals the potential synergistic effect of integrating technologies. In this example, the power of remote sensing and GIS extends far beyond what they would provide as functional but independent technologies.

3. The project exemplifies meaningful and productive cooperation between research and management agencies. Researchers are provided with a well-defined challenge and have the added incentive of seeing clearly how their efforts would be implemented in management. Managers are provided with an equally clear appreciation of the utility of research and technology and can anticipate reaping the benefits in a meaningful time frame.

4. The project is a good example of problem-driven research and development. It links management problems, research development, and technology in a demonstrably significant context. Such a context is critical to make the most productive and efficient use of finite financial resources.

5. Finally, it illustrates how technology should serve the forest community. In my opinion the forest resource is too often used as a context in which to develop technology. Here, technology becomes a vehicle with which to develop the forest resource.

Extension of this approach in the use of technology to resolve other fundamental problems can make a significant contribution towards improving forest management practices in New Brunswick.

REFERENCE

Ahern, F.; Erdle, T.; MacLean, D.; Kireppeck, I. 1989. A quantitative relationship between forest growth rates and thematic mapper reflectance measurements. Int. J. Remote Sens. (In press.)

QUESTION AND ANSWER SESSION

Question for Pierre Bernier by Teja Singh:

My question is for Pierre, a fellow hydrologist, who has been away from the Northern Forestry Centre for a couple of years. I though that maybe he has some perspective, looking back at Alberta as another province in which there is a lot of economic pressure for developing forestry areas with more pulp mills. A number of mills have been announced in Alberta. With these sorts of things coming up, what sorts of pressures do you foresee on forest hydrology modelers? What sorts of demands does this situation make on them?

Pierre Bernier:

Well, the pressures are just as strong as the managers want, to input hydrology into their planning phase. The hydrological concern is one case where you have to convince people that there is a problem or that there is a way to improve management practices. The pressure will come if we do a good job in saying that there is a potential to use hydrology in forestry. If we can convince people that there is a good potential to use hydrology in forestry, then the pressure will be quite great to include hydrological concerns into especially the lower rainfall areas, like the East Slopes in general (and especially the lower end) and also in northwestern or north-central Alberta, in the Grande Prairie area northward where precipitation is fairly low and the practice of opening large clearcuts, for example, might be detrimental to forest growth. I don't know if in northern Saskatchewan or northern Manitoba the same things are true, but I suspect that in any area where you have low summer rainfall conditions and coarse soils, for example, those are the areas that would benefit from the onsite application of hydrology. There is also the site degradation aspect, or the water resource degradation aspect. I think the pressure will become quite great in areas for better environmental assessments of the impact from forestry and assessment of forestry effects on the water resource. In that sense there will be pressure on the hydrological modelers to produce good tools for coming up with these assessments.

APPLICATIONS OF MODELING IN AGRICULTURE PRODUCTION

K.K. Klein
University of Lethbridge
Lethbridge, Alberta

INTRODUCTION

Models are often used in the study of agricultural production systems because a careful examination of the real system is too costly or disruptive, if it is even possible to conduct. Study of the real agricultural system would be very expensive due to the high cost of land, labor, and capital associated with many agricultural enterprises. Of even greater importance is the possibility that experimentation might disturb the real system and result in conclusions being drawn from an artificial situation unintentionally imposed by the researcher.

Unique characteristics of agriculture make the use of models especially applicable to production analyses. Besides being complex, agricultural production is also stochastic and dynamic. Studies of real agricultural systems would have to be repeated in many different locations to provide generally applicable results. To create a controlled environment, studies would have to be repeated over time to account for climatic and other changes in the production environment. Fortunately, variability can be controlled (and repeated) in a computerized model of agriculture. Experimentation in the real world would also be very time-consuming.

If the real system was studied, results would not always be available in time for use by decision makers because of the time required for growth of animals and plants. This would particularly be the case in forestry. Computerized models can systematically examine long-term effects, however.

Agriculture, like forestry, is a complicated industry to understand. Many factors are involved in growing and marketing the products. These factors are often very diverse (e.g., weather conditions, plant genetics, pests, nutrition, economics) yet interrelated. The interrelated factors that affect outcomes in these industries are better understood by examining the entire production and marketing system. Study of the factors affecting production and marketing of agricultural or forestry products requires a multidisciplinary approach. Dent and Blackie (1979) state that agriculture "cannot be properly understood by an 'ad hoc' set of studies of the various elements that make up the system." The interrelationships among the various factors are so important that the whole production and marketing system is more complex than is the sum of its parts.

It is therefore necessary to examine the connections among the various elements of the production and marketing system. It is usually not adequate to understand the growth of a cow or a tree. Growth of these commodities is affected by the growing conditions for forages (in the case of cows), the closeness of other trees of the same or different species, the effects of pests, animal or plant nutrition, and a host of other factors. Depending on economic and growth conditions, it may make sense to cull the cow or harvest the tree at a younger or older age. In addition, governmental policies and programs (like taxation or subsidies) might differ among provinces. Decisions regarding growth of agricultural and forestry products are therefore affected by climatological, agronomic, economic, and political factors.

In this paper, an examination is made of the requirements for a systems-based agricultural model. When designing a systems-based model for agriculture or forestry, a number of things must be considered. The next section explores some of the connections that should be considered in developing and using such a model. Although the focus is on the agricultural industry, many of the same factors would be just as important in forest industry models. The last section contains a brief discussion of two agricultural models and assesses their accuracy in analyses of the agricultural industry.

SOME REQUIREMENTS OF AN AGRICULTURAL MODEL

Objective Criteria

The first problem to be addressed in any modeling effort relates to its purpose. Who is the relevant decision-maker for whom the model is being developed? Is it the individual entrepreneur for his or her use in making production or marketing decisions? Is it the scientist or research administrator who needs information for making decisions on research strategies or for testing hypotheses? It is a provincial government agency that is searching for ways to improve the economic contribution of the agriculture or forestry industry to the province? Is it a federal government agency that might be interested in providing subsidies or imposing taxes on selected parts of the industry to improve economic performance, promote regional development, or provide stability to the industry?

Ideally, a model should be developed in close consultation with the appropriate decision-maker, not only so that it is made more relevant, but also to give the decision maker an opportunity to gain confidence in it. In practice, this desirable goal often is sacrificed due to time constraints or expediency on the part of the model builders. It should be noted, however, that building models in isolation from the decision maker often condemns the resulting model to a life on the shelf, frustrating the model builder and decision maker alike.

The accounting stance is particularly important. It is not as simple as deciding between private and public objective criteria. The basis for examining costs and benefits relates to the decisions that must be made on the basis of the model's manipulations. A provincial government agency has a different perspective than does a federal government agency. Analyses based on total economic returns from particular actions may not be of interest to provincial officials if part of those returns accrue to individuals or companies in other provinces.

Interface Between Products and Inputs

On farms in western Canada, decisions made regarding such variables as crops to grow, rotation, and marketing strategies are influenced by whether or not a livestock enterprise exists on the farm unit. A farm-level model of just the cropping enterprise may not be appropriate for the large proportion of farms that have mixed grain and livestock enterprises. A farmer with cattle must consider the need for a secure supply of fodder and grain for the animals. This type of farmer may take fewer risks on cash crops and plant barley or oats that can be cut for annual forage (green feed) if the perennial forages have a low yield in a particular year.

A small beef enterprise may complement the grain enterprise by using land that is unsuitable for grain production. Expansion of the cattle herd, however, usually results in a reduction in area available for the production of grain or oilseed crops. It may also reduce labor time available during critical time periods, such as during planting and harvesting operations.

The challenge in any modeling effort in the agricultural and forestry industries is to identify the interactions among major products and inputs. Failure to adequately include the effects of other products or inputs can produce misleading results and thus impair the model's usability and credibility.

Time Dimension

All production takes time, and the biological lags in production take on special importance in the agricultural and forestry industries. Annual crops in western Canada are usually planted in the spring, harvested in the fall, and sold throughout the next 10 or more months. The beef enterprise is even more complicated time-wise. It might take 3 years from the time a decision is made to breed a cow until the resulting offspring is ready for slaughter. Moreover, many production decisions can be made during this extended time period. A cattle producer might decide to sell calves at weaning time if forage supplies are short or if prices are relatively high. The producer might put the weaned calves straight into the feedlot to finish them as quickly as possible or maintain the calves over the winter on a growing and maintenance diet. In the spring, the yearling calves might be sold as stockers and feeders, put on pasture for additional slow growth, or placed in a feedlot. The eventual marketing time of these animals is dependent on the route chosen by the producer and on the intensity of the feeding program. Because demand for beef (and hence price) is seasonally affected, the eventual returns could be much different depending on the type of program used by the producer.

Everyone recognizes the time dimension in forestry production. It can take decades from the planting of a tree to its eventual harvest. One of the tasks facing modelers of the forestry industry is to identify the time periods when decisions can be taken about planting, management, and harvest of the trees. Results from a model that do not account for the time lags in production can be difficult to interpret.

Stochastic Versus Deterministic Models

A major consideration in building a model of the agricultural or forestry industries is how to represent variability in prices and yields. The type of solution algorithm that can be used to solve the model is dependent on whether or not the model is stochastic.

In large part, the deterministic versus stochastic decision can be made on the basis of proposed uses for the model. Although stochastic processes may follow actual production and marketing situations more closely, a deterministic model may be more appropriate for many types of analyses. Deterministic models can be solved with a single-valued objective criterion. Stochastic models must have at least two arguments in the objective function. Interpretation of results from stochastic models is made more difficult due to the trade-offs inherent in the multifaceted objective function. Of course, any gain in simplicity of interpretation comes at the expense of fidelity with the actual production or marketing situation being modeled.

Many models are designed for prescriptive rather than descriptive purposes. In these cases, deterministic models may give as reliable results as would stochastic models. The decision maker might be interested in projecting outcomes with pessimistic or optimistic scenarios. Stochastic variables in the model may interfere with interpretation of results from these projected scenarios.

Regional Production Differences

Production of agricultural and forestry commodities are greatly affected by their regional location. This is primarily due to weather, soil, and pest conditions that differ by eco-climatic region. A systems model that does not make provision for regional differences in production may be irrelevant for many types of questions.

Provincial Policy Differences

Models at the national level must include some mechanism to separate the effects of different provincial policies. Each of the provinces in Canada has a provincial department of agriculture. Each also has specific subsidy and taxation schemes that affect incentives to produce and market agricultural commodities. For example, the province of Alberta currently has a subsidy program for users of feed grains. This program is meant to offset the perceived distortions in the agricultural economy from a federal subsidy program on grain transportation that is administered by the Western Grain Transportation Authority. The Alberta offset subsidy program is designed to prompt livestock producers to increase their herds; it therefore affects the quantity of livestock produced for sale in that province. Livestock producers in the other prairie provinces do not receive this offset subsidy. Nevertheless, producers in neighboring provinces may be affected by the Alberta offset subsidy, as it provides incentives for Alberta feedlot operators to bid a higher price for feeder cattle, some of which may be imported from neighboring provinces. (Of course, other provinces have their own, but different, incentive schemes for their livestock producers.)

In industries that face different government policies and programs depending on the province of their location, it is necessary to account for these in an aggregate model. Anything that differentially affects production or marketing decisions should be included.

Transportation of Products to Market

Most of the output from the agricultural and forestry industries in Canada must be transported to other areas where it will be consumed. Destinations might be within or outside of Canada. Farm- and government-level decisions in these industries are obviously affected by the characteristics of markets where these commodities will eventually be consumed. This means that models of national scope should not overlook the transportation alternatives or bottlenecks involved in getting the product to market. This is especially true for commodities such as wheat, the vast majority of which is shipped to overseas locations. In the winter months when ships cannot get through the St. Lawrence Seaway, transportation becomes much more costly. Neglect of transportation constraints of this type may affect the accuracy of any analyses done with a model.

International Connections

A large proportion of forestry and agricultural commodities that are produced in Canada are consumed in foreign countries. Many factors that affect entry of these products into the various countries could have upstream effects on the domestic industry:

import restraints, credit terms, fluctuating exchange rates, transportation rates. In models of the agricultural and forestry industries, these connections can be important and should be considered in the model conceptualization stage.

REFLECTIONS ON TWO AGRICULTURAL MODELS

Brief descriptions of two agricultural models are presented in this section:

1. a farm-level model of beef-forage-grain production, and

2. a regional linear programming model of Canadian agriculture (CRAM).

Complete descriptions of these models have been published elsewhere (Sonntag and Klein 1979; Webber et al. 1986). These models are examined with regard to the important model requirements listed in the previous section.

Beef-Forage-Grain Model

This is a farm-level model that simulates a wide array of production and management strategies for these three enterprises on farms in western Canada. It includes options for six different types of cow-calf enterprises plus the purchase of feeder calves:

1. Cow-calf: sell weaned calves;

2. Cow-calf: sell yearling feeders;

3. Cow-calf-feedlot: weaned calves go directly to the feedlot and are sold as finished slaughter cattle;

4. Cow-calf-yearling-feedlot: weaned calves are placed in a stocker program for about 5 months and are then shifted to a feedlot finishing program;

5. Cow-calf-yearling on pasture: weaned calves are placed in a stocker program for the winter, on pasture the following summer, and are sold off-pasture as short-keep feeders;

6. Cow-calf-long yearling-feedlot: same as (5) except that short-keep feeders are placed in the feedlot and finished to slaughter weight.

Seven types of pasture are included in the model:

1. Native (unimprovable). This represents rough native pastures that are unimproveable due to topography, stones, soil type, etc., and can therefore only be used in their native state.

2. Native (improvable). This includes pasture that is under native vegetative cover but can be improved by fertilization or clearing, breaking, and reseeding.

3. Improved. This represents improved rangeland or cropland that has been planted to species particularly adapted for each of the three major soil zones in the prairie provinces.

4. Irrigated pastures.

5. Community pasture with administered stocking rates;

6. Stubble. This is from annual cereal crops.

7. Hay aftermath. This includes regrowth on perennial hayland.

The model contains three crops: barley, canola, and cereal forage. Many options are available for growth and marketing of these products. For full details see Sonntag and Klein (1979).

How does this model stack up against the requirements listed in the earlier section?

1. Objective Criteria

This is a farm-level model where the focus is on decisions made by the farm manager. Various objective criteria have been used in this model, such as maximizing terminal net worth (after a period of 5-10 years) and maximizing average net farm income. Other private objective criteria could be used for specific applications, such as those suggested by Patrick and Eisgruber (1968). They contend that objectives may shift with age, education, and experience of the farm manager, as well as with level of indebtedness, family obligations, and other considerations.

2. Interface Among Outputs and Inputs

The model pays special attention to the interrelationships among the beef, forage, and grain enterprises and to the resource requirements for each of those enterprises. It is a whole-farm model, i.e., the perspective is that of the farm manager who must allocate resources and make decisions on production and investment strategies simultaneously. Resources required for production of beef cattle, forages, and grain must be allocated jointly among the enterprises. Labor required for one enterprise cannot be used by a competing enterprise. Grain produced on the farm can be sold or used as feed for livestock. This flexibility is important to farmers due to the inherent instability in forage yields. It is included in the model to represent as closely as possible the choices facing the farmer.

3. Time Dimension

Most processes in agricultural production are time dependent. The beef-forage-grain model calculates resource requirements and growth of animals and forages on a biweekly basis for each year of a possible 10-year planning horizon.

The time dimension is a major consideration in this model. Two examples will show the extent to which this important resource constraint is handled in the model.

The model includes 10 classes of beef cattle: male and female calves, two categories of replacement heifers, male and female stockers, male and female feedlot animals, and the breeding herd of cows and bulls. The weight of animals in each of these classes is calculated for each biweekly period. Animal weights are dependent on birth weights, sex, growth rates, and other factors such as weight changes during gestation and parturition. Relative rates of gain for steers and heifers change as they get older. Calves are weaned at a specified time that corresponds to industry practice. Digestible energy and protein requirements are calculated separately for each class of animal on a biweekly basis. Nutritional requirements are dependent on animal weight, rate of gain, and biological function of the animals.

A second example of the use of time in the beef-forage-grain model relates to the pasture improvement component. The model contains five alternatives for pasture improvement, each of which has different time requirements. The first alternative for pasture improvement is the improvement of native range through reseeding with tame grass species. It involves the following activities in 4 successive years:

Year 1
- high stocking rates in the spring and summer on the area to be improved;
- breaking and cultivation to remove native vegetation in the summer or fall;
- fencing and water development; and
- seeding with early or late season species in the fall if breaking is done in the summer.

Year 2
- seeding in the spring if breaking occurred during the previous fall;
- no grazing in the brown or dark brown soil zones; and
- late fall grazing in the black soil zone.

Year 3
- late fall grazing in the brown and dark brown soil zones; and
- normal grazing in the black soil zone.

Year 4
- normal grazing in all soil zones with yields and rates of use at the same level as improved pasture.

The other pasture improvement alternatives have similar time implications.

A management strategy to increase the size of the beef herd and at the same time develop more secure and higher-yielding pasture supply is complicated to evaluate without the use of a systems model with this type of time accounting. Not only must some native pasture be sacrificed in the 3-4 year period prior to availability of the improved pasture, but extra replacement heifers must be retrained, bred, and added to the breeding herd for this expansion. The extra retention of replacement heifers reduces cash receipts for a couple of years. The cutback in native pasture comes at a time when there is a demand for extra pasture. This means that resources elsewhere on the farm must be diverted to obtain this additional feed requirement. An investment decision of this type can have significant effects on all enterprises on the farm and on the economic performance of the business itself.

4. Stochastic Production

Yields of forages and grains are highly variable and are strongly correlated with growing season rainfall. In the beef-forage-grain model, yields can be specified by the user (and thus the model is used in a deterministic sense) or drawn from a standardized distribution of yields (in which case the model is used in a stochastic sense). For the pasture resource, yields are also affected by the condition of the pasture (yield variability is greater when the pasture condition is poor than when the condition is good), season of use (higher yield with delayed use of pasture), and pasture deterioration (later use means more deterioration).

The beef-forage-grain model has the capability for analyses involving uncertain outcomes of this kind. It does not, however, deal with stochastic biological growth of the beef animals. Because cattle are treated as a group and not individually in the model, it is assumed that interanimal variation is cancelled.

5. Regional Production Differences

The beef-forage-grain model contains some technological specifications that vary by soil zone. The pasture improvement component (mentioned above) is one example of this regional distinction. Others include differential yields, number of tillage operations on summer fallow, pre-seed tillage operations, and size of machines purchased for replacement.

6. Provincial Policy Differences

In the beef-forage-grain model, the only differentiation in provincial programs that is included is the provincial income tax rate. Specific provincial subsidies and taxes for the three enterprises are not included. This is an obvious area for model improvement.

7. Transportation

The beef-forage-grain model stops at the farm gate. All prices used in analyses of farm-level decisions are those given to the farmers after all deductions have been removed. No transportation activities are therefore included in this model.

8. International Connections

There are none in this farm-level model.

Canadian Regional Agricultural Model (CRAM)

CRAM is a fairly large linear programming model of Canadian agriculture. It contains about 1500 activities and 900 constraints.

CRAM is a regional model that includes five geographical levels: nation, east and west Canadian, provincial, crop region, and export points. Nation refers to all of Canada, which is subdivided into two zones, western and eastern. There are seven provincial groups: British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and the Atlantic provinces. The model includes 29 crop regions, 22 of which are in the prairie provinces: seven in Alberta, nine in Saskatchewan, and six in Manitoba. Each of the other seven provinces is modeled as a single crop region. Two export terminals, Vancouver and Thunder Bay, are defined in the model.

Two major sets of production activities are defined—those dealing with crops and forages and those dealing with livestock. Crop and forage production takes place in each of 29 regions; livestock production is defined at the provincial level for the seven different provincial groups. Principal categories of crops include grain, forage crops, pasture, and other crops. Four sets of livestock are included—beef, dairy, hogs, and poultry.

Trade and transport activities in the model specify the shipment of grains from production region to domestic and export demand points. Likewise, transport activities for live and dressed meat are defined for movement of those livestock categories among provinces and to export points.

1. Objective Function

The objective function in this model is to maximize net revenue to the agriculture sector in Canada. The model takes a national perspective, so solutions may not maximize net revenue to agriculture in a particular province. The user of the model must be aware of how this type of objective function changes the interpretation of economic evaluations done with this model.

2. Livestock-grain Interface

A large part of the CRAM model is concerned with connections among major agricultural products in Canada. Four livestock groups (beef, dairy, hogs, and poultry) are modeled in each of the seven regions. Forage, pasture, and feed grains produced in each province are available for feed for the livestock categories. Provincial deficiencies of feed can be met by imports from other provinces.

The model optimizes the use of all available resources simultaneously. This means that livestock and grain products are considered together and not separately when the model is being solved.

Although the CRAM model is meant to optimize the use of all available resources in agriculture, certain restrictions in the present version of the model prevent the wholesale movement of resources from one enterprise to another. Land cannot be transferred from annual to perennial crop production. There is little interaction among the livestock groups, except in their competition for supplies of feed; however, this agricultural model could be extended to include these types of interactions.

3. Time Dimension

The present version of the CRAM is a static one-year model. All accounting of costs and revenues is done on an annual basis. Because it is a static model, there is no time path of adjustment like that in the beef-forage-grain model. Given the starting conditions and a set of prices, an optimal solution to the model represents the final picture after all adjustment has taken place. For this reason, the age distribution of livestock must be established prior to operation of the model (i.e., proportion of calves placed in the feedlot, proportion on a maintenance diet, etc.). This is necessary to permit an evaluation of inventory at the beginning and end of the year. The linear programming algorithm used to solve this model will permit a recursive, multi-year model. Adding one or more extra years to this model would not only require a bigger modeling effort but would make the model very much larger and more costly to solve.

4. Stochastic Production

All data in the CRAM are fixed. No stochastic elements are included, but with adjustment of yield or price data and multiple runs, the model could be used to provide information on uncertainty of outcomes.

5. Regional Production Differences

CRAM is a regional model, and its major strength is in analyses of interregional differences. As noted earlier, the model includes 29 crop-producing regions in Canada, 22 of which are in the three prairie provinces. As well, livestock production occurs in seven regions of the country, one for each province west of the Maritimes, and one for the Atlantic provinces. Regional production differences are expressed in various technical coefficients, yields, prices, transportation costs, and resource constraints.

6. Provincial Policy Differences

The CRAM model has been used to evaluate the effects of provincial subsidies in the Canadian beef and hog industries (Graham et al. 1988). The structure of the model makes the assessment of these types of provincial policies extremely easy.

7. Transportation

A major component in CRAM is transportation. Shipments of grain from each of the crop-producing regions to Vancouver and Thunder Bay and to domestic markets are specified. Livestock and meat products can be transported among any of the provinces as well as to export. Analyses can be conducted on the effects of transportation rates on agricultural production and net returns in any region in Canada (e.g., see Klein et al. 1986).

8. International Connections

CRAM is a national model. The international connection is modeled through prices for export products. There is no feedback mechanism that causes prices of internationally traded products to change with changes in export quantities.

CONCLUSION

Many different types of models have been developed in the agricultural and forestry industries. Although a great deal of resources have been expended in the construction of most of these models, their subsequent use has often not justified their high cost. This may have been due to many factors. The major reason, however, is usually the lack of consultation between the decision maker and the modeler or researcher. To instill confidence in the model, the modeler or researcher must work closely with and anticipate questions by the decision maker. This is not an easy process. The decision maker usually has more immediate concerns and often has little patience for the slow and tedious job of model construction. This is not an easy problem to solve. No solutions are offered here; attention is simply drawn to this problem that affects the usability of models in the forestry and agricultural industries.

Construction of production and marketing models in the primary sectors, like agriculture and forestry, always begins with a conceptualization of the system being modeled. It is at this stage that important considerations of objective functions, product and input interrelationships, time dimension, stochastic nature of production, regional production differences, provincial policies and programs, transportation of products to market, and international trading environment need to be addressed. To make the models as useful as possible to decision makers an attempt must be made to consider these points in a systematic fashion. It may not be possible (or even warranted) to include all of these factors in a single model, but it is important to consider the boundaries of the production or marketing system being modeled so that important variables and constraints are not omitted.

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USING CLIMATIC CHANGE SCENARIOS TO MODEL AGROCLIMATIC AND ECOCLIMATIC CONSEQUENCES

E.E. Wheaton
Saskatchewan Research Council
Saskatoon, Saskatchewan

ABSTRACT

The importance of having adequate methodologies to assess the impacts of climatic change and variations on ecosystems cannot be overemphasized. Even without a change in climate, much work needs to be done to define and verify the basic relationships between climate and ecosystems. As the probability of a change in climate increases, the need for the best modeling efforts becomes imperative. This paper explores several methodologies, including the design of climatic change scenarios, the selection and improvements of impact models, the sensitivity analysis of impact models, and the use of systems analysis. The main climatic change scenarios used are based on Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model results. Some of the potential changes in climatic resources for agriculture and forestry are presented. The number of growing degree days shows an increase for both the GISS and GFDL representative grid points. This may result in the northward shift of the boreal forest ecoclimatic zone and an expansion of the climatic zone suitable for grassland and agriculture. The enhanced greenhouse climate, as indicated by the GISS doubled carbon dioxide results, would reduce spring wheat yields by about 16% and cause considerable economic losses unless preventative plans were engaged. Such a climate might reduce wind erosion potential and increase average potential biomass productivity, but at the same time droughts could become more frequent and severe. Climatic warming without increased precipitation would cause all impacts to be generally adverse and more intense. These studies are only the beginning of the work that should be undertaken in the area of climatic changes impact assessment.

INTRODUCTION: THE REASON FOR CONCERN

Human beings are altering the composition of the atmosphere at an unprecedented rate. If present trends continue, the combined concentrations of atmospheric carbon dioxide and other greenhouse gases would be radiatively equivalent to a doubling of preindustrial carbon dioxide levels as early as the 2030s (WMO 1985). That time is not too far down the road, especially if we are examining the climatic response and possible effects and are planning for these changes.

How is the atmospheric composition changing? The amounts of trace gases in the lower layer of the atmosphere are increasing. These gases include carbon dioxide, nitrous oxide, methane, ozone, and chlorofluorocarbons (Bolin et al. 1986). These gases act like a greenhouse because they are relatively transparent to incoming solar radiation, but they absorb the heat energy emitted from the earth. It is very important to explore the climatic consequences of an enhanced greenhouse effect.

This paper includes an examination of hypothetical future climates and their design, impact assessment, and possible effects on climatic resources for agriculture and forestry.

CLIMATIC CHANGE AND VARIATION SCENARIOS

Selection and Design

Various types of climatic scenarios can be used to depict a warmer or changed climate as may be expected with an increased amount of greenhouse gases. A climatic-change scenario has been defined as a description of the spatial patterns and seasonal behavior of temperature, precipitation, and other important meteorological variables in an altered climatic state (Santer 1985). Climatic-change scenarios of various types have been used. I have designed a classification to characterize these as follows: 1) historical and areal analogues, 2) synthetic, 3) General Circulation Model (GCM) derived, and 4) hybrid climatic change scenarios (Maybank et al. 1987).

Historical analogues are especially useful if there is a sufficient length of record for the selection of anomalous periods, or they can be constructed from paleoclimatic data based on proxy information such as that from tree rings, ice cores, etc. A set of these scenarios can be quite flexible as they can use single anomalous years, an extreme decade, or an extreme period of years. They also have the advantage of representing conditions that actually occurred in the past. In addition, because they can occur in the next season or year, these scenarios may have greater implications for the near future than do the GCM scenarios of enhanced CO_2, for example.

Scenarios based on past records of climate may not be as suitable, however, in the context of changes in atmospheric chemistry. Because such elevated levels of radiatively active gases have not occurred in the historical past, the warmer historical periods must have been caused by other mechanisms. They may therefore not even come close to duplicating the characteristics of a warmer climate caused by the greenhouse gases. Also, the projected warming may be greater and more uniform globally than during any period in the historical record.

Synthetic climatic change scenarios can be created by combining or adjusting historical data. A synthetic series can be created by selecting single anomalous years, seasons, etc., and placing them consecutively in a sequence. This type of scenario can also be constructed by adjusting historical data by increasing temperature arbitrarily by a certain range of degrees and increasing rainfall by certain percentages, for example. This may be one way of forcing the historical data to conform to what may be an enhanced greenhouse gas level. But it may result in the analysis of an excessive number of combinations of temperature and precipitation, some of which may have a low probability of joint occurrence and may not have greenhouse gases as the driving mechanism for the change.

Some climate impact modelers have therefore turned to the GCM simulations to provide sets of perturbed climatic data as inputs to impact models. The GCM results provide a powerful technique to explore the nature of climate in a warmer world because they overcome many of the problems inherent in the use of the previously mentioned types. Their usage also entails advantages not mentioned above: 1) data are provided on a uniform grid-point basis so the network uniformity is optimum, and 2) data are simulated that may not exist at some stations (e.g., some stations do not have precipitation records).

There are, however, several problems in using GCM results in esti-mating climatic impacts. One of these is that the $1 \times CO_2$ results often do not conform well to the observed climate (Williams et al. 1988; Wilson and Mitchell 1987). It is usually inappropriate to use GCM results for $1 \times CO_2$ and $2 \times CO_2$ directly as inputs to impact models. This problem may be overcome by using the difference between (for temperature) and ratio of (for precipitation) the $2 \times CO_2$ and the $1 \times CO_2$ GCM results as adjustments to historical data. The historical data and the adjusted data are then used to simulate the $1 \times CO_2$ and $2 \times CO_2$ climates. It is hoped that the comparison between the two simulations better indicates what the perturbed climate could be like. Modelers of GCMs are also striving to improve their ability to simulate climatic reality given the complexity of the atmospheric-oceanic-geographic (e.g., vegetation, land form, hydrology) system to be modeled and of the computer requirements of such work.

Another problem with using GCM results is that data that have been calculated for climatic parameters such as wind, atmospheric circulation, and evaporation may not be available to those doing the impact studies. This problem is decreasing as communication between the GCM and impact modelers increases.

Inadequate spatial resolution is also a limitation of GCM results. Data are not available for the smaller regional areas but only for widely spaced grid points. Spatial interpolation can be used in calculating the differences or ratios for applying the historical data for small areas (Williams et al. 1988), but this does not overcome the basic problem of lack of sufficient spatial resolution of GCM results.

Inadequate temporal resolution is another shortcoming of GCM results. Data are available only as monthly or seasonal means. A knowledge of extreme events and their frequencies rather than just means is also useful to impact modelers and is economically significant; examples are frost and strong winds (Wilson and Mitchell 1987).

Little or no information exists regarding the statistical distribution of the climatic parameters (distribution type, variation, etc.) as GCM results. Use of the GCM results, without this information, also entails invoking several assumptions, such as that the changed climate will have the same variability as the past climate.

More information is needed about the climatic response to an increase in CO_2 and the other greenhouse gases over time (Santer 1985). This would provide more than just a snapshot in time at the $2 \times CO_2$ level. Results of GISS are now available in intervals of a decade, and climate impact modelers should make use of these.

The use of hybrid climatic change scenarios can sometimes be more realistic than employing those based on the GCM results alone. The Canadian team of the IIASA/UNEP Climate Impacts Project (Williams et al. 1988) used this type in agricultural impact assessment. These hybrid scenarios are an effective combination of two or more types, such as the GCM-based scenarios for some parameters and historical or synthetic data for others.

Hybrid climatic change scenarios are especially useful when some necessary parameters for an impact model are not available from the GCM results or when a parameter has been modeled with somewhat less confidence than is desired. For example, Williams et al. (1988) used a combination of temperature adjustments based on the Goddard Institute for Space Studies GCM experiments (Hansen et al. 1984) and historical precipitation data. Hybrid scenarios can help overcome the spatial, temporal, geographic, and snapshot problems encountered when using the GCM results only. So, while the climatic modelers proceed to improve the GCMs, the impact modelers also have a wide variety of techniques to use in making the much needed improvements in their own modeling.

Climatic Change Scenarios Chosen to Simulate Climate for $2 \times CO_2$

The climatic change scenarios discussed in this paper are the GCM-derived hybrid type that utilize both the normal and GCM climatic data as discussed previously. The $1 \times CO_2$ and $2 \times CO_2$ GCM equilibrium climate adjustments (differences for temperature and ratios for precipitation) and the normal climatic data for grid points including the study area were provided by the Canadian Climate Centre. The GCM results are from experiments undertaken by the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL). The climatic change scenarios based on these models are therefore termed GISS1 and GFDL1 for ease of discussion and presentation.

The other climatic data required for the impact models were not available from the GCM results. Thus the most recent climatic normals and standard deviations from Environment Canada's Atmospheric Environment Service (1982, 1984) publications were used, whenever available. Gridded normals were provided by the Canadian Climate Centre[1].

The GCM results were also used to create hybrid climatic-change scenarios. Temperatures were increased as for the GISS1 and GFDL1 scenarios, but the normal precipitation values were used. These scenarios are termed GISS2 and GFDL2. They were selected because the projections of precipitation amounts from GCMs are less certain than temperature projections, and the precipitation projections can be high compared to historical data. Historically, high temperatures have been found to be associated with low precipitation amounts for prairie locations (Villmow 1956; Robertson 1974).

A reference is needed against which results of analysis involving these scenarios can be compared. The reference used is the standard climatic scenario based on the most-recent normal period, 1951-80 (termed HIST).

Climatic Characteristics of the Scenarios

The basic characteristics of the temperature and precipitation of the scenarios are briefly described in this section to provide a foundation for examining the results of the climatic models that are based on the temperature and precipitation data. The characteristics of the temperature and precipitation data are displayed through time (season) and space in Wheaton et al. (1987).

[1] Personal communication from R. Street, Canadian Climate Centre, Atmospheric Environment Service, Downsview, Ontario, 1987.

Temperature and precipitation of the GISS- and GFDL-based scenarios are examined using graphs of the seasonal distribution of the monthly means for representative grid points and maps of the spatial pattern across the study area.

Temperature Characteristics as Depicted by the Climatic Change Scenarios

The seasonal distribution of the climatic-change scenarios is examined by means of plotting the mean temperatures against time (months) for the eight representative points mentioned previously. The most noticeable characteristic is that the lowest increments above normal are projected for the summer months for both scenarios. A difference noticed is that although GISS projects the greatest increments for the winter months (often in December) at about 6-9°C, the largest GFDL increments are for the spring months (often in April) and are about 6-7°C. Also, the GISS temperature increments depict a more uniform change from month to month, and the GFDL month-to-month changes are much more erratic. This effect is possibly because the GISS results have been interpolated from a coarser grid space and reflect this smoothing.

A result of the lower increase of temperatures in the summer months as compared to the winter months would be that the winter-to-summer change would not be quite as drastic. Continentality can be measured by the difference between the average temperature of the warmest and coldest months and by the latitude of the location. Thus the climatic-change scenarios depict a climate that is less continental, that is, more maritime than the current climate of the study area.

Maps of isotherms for the key months of each season and for each of the two main climatic scenarios were used to explore spatial distributions in the report by Wheaton et al. (1987). An obvious difference between scenarios is that the increments above normal are greater with the GISS than the GFDL scenario, especially in winter.

Precipitation Characteristics as Depicted by the Climatic Change Scenarios

As for temperature, seasonal and spatial patterns of the precipitation climate were characterized with the aid of graphs and maps. Again as for temperature, the seasonal distribution of the mean monthly precipitation amounts for the GISS-based scenario is more uniform than for the GFDL-based scenario. The month of maximum precipitation does not change with the projected climatic changes but continues to be July for much of the study area, except for the far south and the far north, which have June and August maxima.

The amount of precipitation is expected to change with CO_2-induced climatic change as described by these scenarios. Both of the scenarios show an increase in precipitation for most months, in general. Exceptions exist, that is, decreases of precipitation are projected for both scenarios especially for the fall for GISS and for both summer and fall in the GFDL-based scenario. The GFDL-based scenario has the greatest ratios of change, both as increases and decreases, compared to the GISS-based scenario. Again, GISS1 has a much more uniform precipitation climate than GFDL1.

Maps of the isohyets were used to explore and compare spatial patterns for the GISS1 and GFDL1 climatic scenarios in Wheaton et al. (1987).

IMPACT ASSESSMENTS

Selection of Impact Models

In situations where one is fortunate enough to have impact models to choose from it is advisable to have a set of selection criteria upon which the choice is based. The criteria can also be kept in mind while developing models.

A useful discussion of the selection of impact models appears in Williams et al. (1988) and Wheaton et al. (1987). The selection criteria they used included relevance to the study area; variation of capabilities, model assumptions, and data requirements; suitability for macroscale analysis and sensitivity to changes in the variables analyzed; existence in a practical, operational form; and efficiency and economy of use.

The above criteria along with several others can be put in matrix form against the names of the models to aid in their comparison. The other criteria deemed suitable include whether the data requirements are realistic, whether they are physical or empirical, their degree of flexibility and documentation, and whether or not they use climatic data. This assessment can help select the most promising models for impact assessment. Also, much information about the models can be effectively conveyed to the reader or user if such a matrix is provided.

Climatic-, Growth-, and Productivity-Impact Models Used

Several climatic-impact models were used for the climatic change impact assessment in Wheaton et al. (1987). The modeled results include growing degree days (0 and 5°C thresholds), precipitation effectiveness, and the climatic index of agricultural production (CA) along with the numerous factors used to calculate CA such as the soil moisture deficit, evapotranspiration, and the dryness, solar, thermal, and heliothermic factors.

Only the growing degree days were calculated for all of the grid points in and surrounding the study area because of time limitations; therefore at least one representative point was chosen to provide data for each forest zone for each of the scenarios. All of the appropriate grid points should be used in future analysis, if possible, to better assess spatial patterns.

Growing degree days (GDD) are selected because of their long history of characterizing the thermal climate for vegetation, both in Canada and internationally. They are indicative of both growing season length and temperature and have been used in another climatic change impact on forestry study for similar reasons (Kauppi and Posch 1988).

The precipitation effectiveness index of Thornthwaite (1931) is also calculated from a relatively simple model, and it uses available data and is suitable for displaying spatial patterns. It is a function of both temperature and precipitation, in which evaporation is expressed in terms of temperature and is derived from empirical data. An advantage of this index for our purposes is that it was designed for a climatic classification in relation to vegetation and soil classifications and is useful for characterizing spatial patterns of large areas. Newer versions of this model with modifications to improve relevance to the study area should also be examined.

The climatic index of agricultural potential (CA) (Turc and Lecerf 1972) reflects both thermal and moisture resources and is computed by summing the 12 monthly products of heliothermic and moisture factors. The heliothermic factor (HT) includes both temperature and solar parameters. The soil moisture factor (Fs) is computed using precipitation and temperature in a climatic soil-moisture budgeting procedure.

The soil moisture factor is 0 for very dry conditions and increases to 1.0 for plentiful moisture; excesses of moisture are ignored. The heliothermic factor has only a lower limit; it is 0 where the mean daily minimum temperature for the month is 0°C or lower, and at higher temperatures it increases with increasing temperatures. Thus CA reflects the length of the growing season and the amount of heat and moisture available to plants during the season. It is indicative not only of the agricultural potential of the climate but also of the potential for biomass productivity in general, including hay and forest productivity, for examples (Turc and Lecerf 1972).

Another advantage of this model is that it can be used to explore changes in biomass in general and is not limited to one vegetation type. Considering that climatic change may be accompanied by a shift in vegetation zones, this capability is very appropriate.

The term biomass productivity used here is equivalent to total harvestable dry matter, which would include the weight, after drying, of all plant material. Turc and Lecerf (1972) suggest that each unit of CA is equivalent to dry matter production of about 0.6 t/ha. This value can then be adjusted by a harvest index to indicate the harvestable timber quantities, for example.

Monthly and annual values of CA, Fs, and HT were computed for grid points in the study area for several climatic-change scenarios and for the normal climatic data. The required data include monthly averages of daily mean temperature, daily minimum temperature, monthly total precipitation, average monthly global solar radiation, and median monthly day length. The solar radiation data were not adjusted, so the assumption is that the solar radiation remains the same. The mathematical basis of CA is explained in detail in Williams (1985) and Williams et al. (1988).

MODEL RESULTS AND CONCLUSIONS

Several indexes or models were used as discussed previously to analyze the impacts associated with the climatic-change scenarios. Effects on the thermal climate (growing degree days), the moisture climate (precipitation effectiveness), and the combined thermal-moisture effects (climatic index of agricultural potential, which reflects biomass potential) for each of these indexes or models for each climatic change scenario are shown in Table 1.

Growing degree day (GDD) results indicate an increase of 35-48% for the GISS scenario representative grid points and 13-40% for the GFDL representative grid points as compared to the normal GDDs. To provide an idea of the implications, the thermal resources for forestry at location B (54°N, 105°W) in the predominately forest zone become 48% greater than average or 1829 GDD with the GISS scenario. This value is similar to that of locations in North Dakota, for example.

A similar location for the GFDL scenario would have GDD amounts similar to those of southern Saskatchewan in the semi-arid grasslands. If the growing season thermal resources on a long-term basis increased to the levels indicated by either of these climatic change scenarios, the climate could be more suitable for grassland vegetation for a large portion of the study area. The implications of these increases for forest species, zones, and forestry are important and should be further explored for the western boreal forest.

Another way to estimate impacts is to examine shifts in the position of zones. The zones that we are interested in are the ecoclimatic or climatic characteristics of ecological zones including the grassland and forestry zones, for examples. The 600- and 1300-GDD isolines approximate the current northern and southern boundaries of the boreal forest (Kauppi and Posch 1988). One can estimate the shift in position of the ecoclimatic zone using this method. Both scenarios show considerable shifts in the forest zones using the above relationship, with the GISS scenario producing the greatest shifts because of the higher temperatures (Figs. 1 and 2).

The GISS scenario shows the northern limit of the boreal forest climatic zone shifting 320-400 km north as indicated by the 600-GDD isoline in much of the west and shifting about 160 km northward in much of the eastern half of the study area. The southern boundary of the boreal forest climatic zone as delimited by the 1300-GDD isoline shifts northward of its current position to about 711 km in the west and to about 1100 km in the east.

The GFDL scenario suggests that the northward shift in the northern boundary of the boreal forest climatic zone would be about 240-300 km in the west and only 80 km or less in the east. The northward shift of the southern limit of the boreal forest is estimated to range from about 700 km in the west to about 1190 km in the east. The implications of these potential shifts are quite serious and should be explored. Implications for planning should be considered and assessed.

The results for the annual precipitation effectiveness index suggest that the mean moisture resources for forestry would increase by 3-22% for the representative GISSI grid points and by 6-17% for all but the most northerly of the GFDL1 grid points, which showed a decrease of 6% below normal (Table 1). The possibility of increased moisture stress that is associated with higher temperatures therefore may generally be offset by the increases of annual precipitation that are estimated by the GISS1 and GFDL1 scenarios. This analysis is for an annual basis, and the seasonal timing of precipitation effectiveness is very important to vegetative growth and should be examined.

When the normal precipitation amounts and the temperature increments of the GCMs are used as in GISS2 and GFDL2, however, both scenarios exhibit decreases for precipitation effectiveness for all the selected grid points. This implies that if the precipitation does not increase along with the temperature the moisture resources would deteriorate. Some species could be adversely affected, but others that are limited by excessive moisture could have improved growth. Precipitation effectiveness should be calculated by month for all the available grid point datasets and then mapped to study the remainder of the study area. The meaning of these changes for the forest should also be assessed.

These studies have generated more questions than answers, as can be expected with preliminary assessments. These challenges must be accepted in research towards the goal of optimum planning for this valuable forest resource.

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Table I. Climatic-change impacts (as percentage change) in relation to normal climatic values[a] (Source: Wheaton et al. 1987)

	GISS1 (2 × CO_2TP)[c]	GISS2[b] (2 × CO_2T)	GISS1 (2 × CO_2TP)[c]	GISS2 (2 × CO_2T)	GFDL1 (2 × CO_2TP)[c]	GFDL2[b] (2 × CO_2T)	GFDL1 (2 × CO_2TP)[c]	GFDL2 (2 × CO_2T)
	Location A (58°00'N 100°00'W)		Location B (54°00'N 105°00'W)		Location C (58°00'N 120°00'W)		Location D (50°00'N 100°00'W)	
Growing degree days (GDD)	+35	+35	+48	+48	+39	+39	+ 38	+38
Precipitation effectiveness index (I)[d]	+22	−10	+12	−10	+19	− 8	+ 3	−11
Dryness factor (Fs)[e]	+21	+ 4	−12	−21	− 3	−17	+ 4	−11
Heliothermic factor (HT)	+44	+44	+33	+33	+54	+54	+ 21	+21
Biomass potential (CA)	+58	+17	+19	− 2	+53	+27	+ 1	−12
	Location E (64°24'N 120°00'W)		Location F (55°30'N 105°00'W)		Location G (59°54'N 120°00'W)		Location H (51°06'N 112°30'W)	
Growing degree days (GDD)	+40	+40	+31	+31	+34	+34	+ 13	+13
Precipitation effectiveness index (I)[d]	− 6	− 8	+16	− 7	+ 6	− 9	+ 17	− 8
Dryness factor (Fs)[e]	−28	−28	+19	+ 4	+10	− 4	+ 2	−24
Heliothermic factor (HT)	+44	+44	+26	+26	+55	+55	+ 46	+46
Biomass potential (CA)	+22	+13	+39	+ 5	+46	+13	+118	+44

[a] Values are the percentage increases or decreases in relation to the mean climatic values for the 1951 to 1980 standard period (HIST). Grid point locations are shown in Figure 1 of the main report. They are different for GISS and GDLD and are chosen to represent main forest zones.

[b] Scenarios GISS2 and GFDL2 use normal precipitation means.

[c] T = temperature; P = precipitation.

[d] Thornthwaite (1931) methodology.

[e] Higher values of F indicate less dry, i.e., more moist conditions.

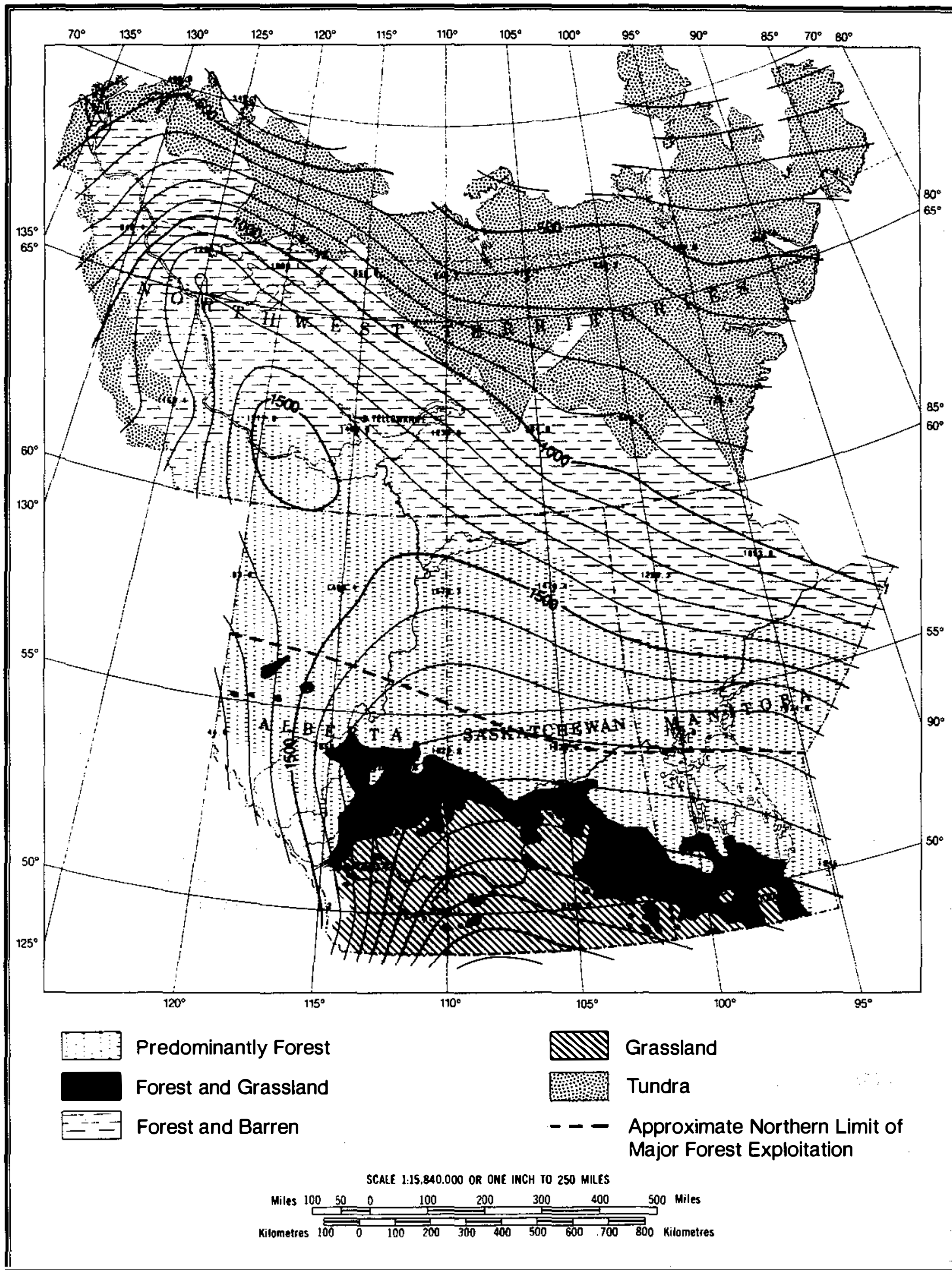

Figure 1. Mean annual growing degree days (above 5°C) for the GISS-based climate change scenarios.

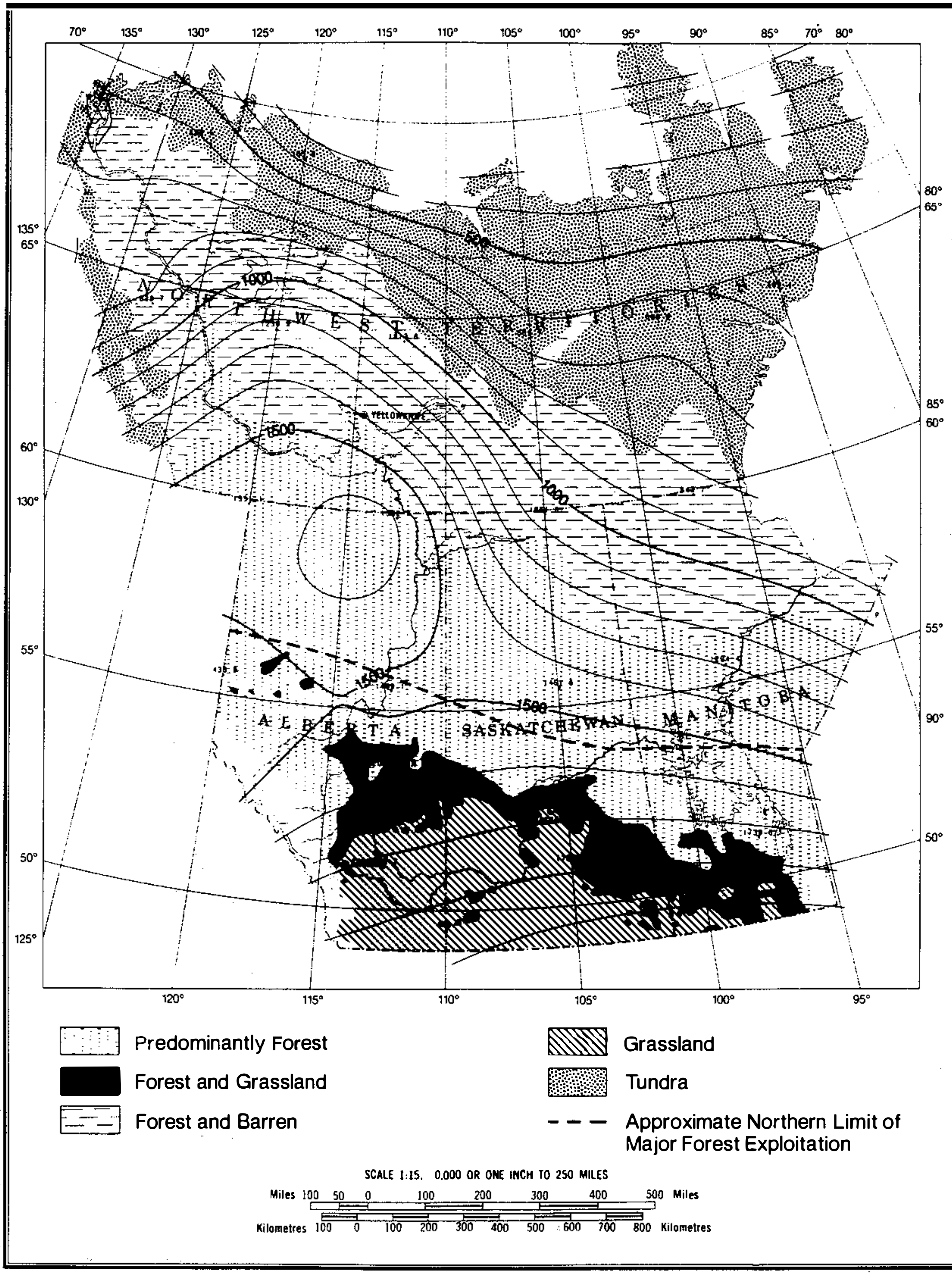

Figure 2. Mean annual growing degree days (above 5°C) for the GFDL-based climate change scenarios.

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QUESTION AND ANSWER SESSION

Teja Singh:

I was part of the team, as Elaine said, who worked together trying to see what sorts of changes are being predicted by general circulation models and what sorts of impacts they will have on forestry, in particular. I was really surprised. I had done some work already, independently of the work that I did with Elaine, on the climatic trends in the boreal forest. I had taken data from 101 stations spread over the boreal forest and dating back 100 years. I found to my surprise, before I heard of the greenhouse effect, that there was already a warming trend being shown by the historic data in the boreal forest. I checked and rechecked my calculations again and again. I am a biometrician at the lab, and I didn't want to put my name on a report for which I may repent later on, but I certainly found that those things were true. Then I began to hear about the greenhouse effect. I personally feel that there is quite a change taking place. There are all indications that people who are competent (I'm a forester, but the people who are climatologists, who take that sort of responsibility), say that change is taking place in terms of temperature. When you shift the temperature gradients, there are also changes involved with it in precipitation, storm patterns, and all these things. If they are right in what they are predicting, then we foresters have to take a very serious look at the implications. I also found that the boreal zones that I took in my study earlier differ by mean annual temperature difference of only two degrees, and that's well within the prediction that they are making. The boreal forest delimitation is 1300 growing degree days in the south and 600 degree days in the north. Then the stress will be on trees growing in the southern limits to cause this shift in the boundaries.

Here is my comment that I would like to share after having built up that background: when the trees are growing under stress and are being pushed for a possible change northwards, then there will be increased fuel loads and increased incidence of insects and diseases because new species will be moving into those areas. There's a general displacement of the overall ecosystem, and these things create really a hazard or a risk, for which we should be well prepared in time. I think that also we have to keep a perspective. Here could be the fire-fighting guys trying their utmost to spend millions of dollars, or whatever amount is involved, trying to save an impossible situation, if I may say. These things have to be planned way ahead and well thought out way ahead so that we are not involved in wasteful expenditure but in trying to retain our focus on species that have ultimate leadership. Mind you, at the end of the glacial age last time, the southern limit for the boreal was as far south as Tennessee. It took all that time for it to reach where it is now. But the change that is being discussed now is very actively and very well supported by EPA and other reports. They all say that if that change is coming, then it is the fastest, 40 times as fast as anything that has happened in the past. Our species are not really prepared or adapted, evolutionarily or otherwise, to take that sort of big change.

Question by Ed Packee:

I've got a question, or more of a comment with a question to follow. I've looked at this question, without looking at the last 30-year normal. I've looked at three areas: the west coast; northern Alaska, Yukon, and Northwest Territories; and the Big Woods in Minnesota. I seem to have found that maybe what we're looking at is an artifact of data based on the last 30 years and 100 years. If you've read Captain Cook's journals, you'll find that Glacier Bay, Alaska, had ice all the way out, as late as 1792, into the salt water. It now goes back into British Columbia territory. The point that I'm trying to make here is, are we really looking at a greenhouse effect (and I'm not disputing the concept), or are we looking at the recession of cold temperatures northward as a result of that little glaciation? Minnesota's Big Woods are not old-growth maple; that's the first forest of maple of any extensive size there. I look at the west coast of Vancouver Island, and I see some of the same things. Then I go up into the arctic, and I see the tree line is receding, coming south. That's based on larch stumps that are very old. I'm just wondering, do we have a greenhouse effect or are we looking at an artifact of the last 100 years?

Elaine Wheaton:

It's probably not an either/or situation. As with many of the natural systems, it's more likely a combination of these. That's a challenge for us to try to straighten out, to make sure what portion is due to the enhanced greenhouse effect and what portion indeed is natural variability, not only of the climate but also of the ecosystem's reaction to that change in climate.

Hamish Kimmins:

I'd like to challenge that a bit. I think you have to look at the mechanisms involved. If you look at the human population growth and the impact of the human population growth on the carbon dioxide budget of the atmosphere and the other greenhouse gases, I think we have to conclude that this is more than the normal climatic variation. Ice ages come and go, but we have accelerated the processes by which ice ages come and go.

SYMPOSIUM SUMMARY

J.A. Beck
University of Alberta
Edmonton, Alberta

I believe Dr. Kimmins set the stage well in tbe keynote address where he indicated we must demonstrate sustainable *development in forestry*, and to do that we must accurately predict *future stand dynamics*. He presented strong arguments that were reinforced by Dr. Wheaton's presentation that the future will not be like the past. Because of this, old bioassay models will lead to incorrect predictions, and either new stand dynamic models are needed or the bioassay models must be modified to take account of a different future.

Almost every model presented at this conference was grounded or based on a prediction of future stand conditions. As such, the decisions they are designed to support would be highly suspect unless the concerns of Dr. Kimmins are addressed. These include the models regarding national timber supply, allowable cut models, timber supply models, silvicultural investment decision models, wildlife habitat models, operational cut models, fire management systems models, inventory update models, harvest scheduling models, and stand investment models. National and provincial public sector decision makers and company decision makers select among alternatives in forestry that almost always depend on these forest stand dynamics predictions.

Underlying this, we as a forest modeling community are responding to a tremendous demand for decision support system models in a wide range of areas. Some overlying demands and trends appear to be consistent as well in that we seem to be developing the following:

1. personal computer-based models;
2. user friendly models (often menu driven);
3. models developed with user or operations input into design;
4. models that look at modeling our operations both more realistically and more holistically; and
5. models that give a visual picture of outputs or the forest (GIS).

Modeling is clarifying and identifying data needs and data gaps that we have if we realistically want to support decisions with more complete analyses.

Another idea that came out several times, either explicitly or implicitly, is that models are an incomplete representation of the real world and we can always make them better. One need only remember Forcyte 1, 2, ... 11.4, with 12 to be developed, to see what I mean. Statements like "Forcyte 10 is dead," however, make one wonder, "which do I use?" or "when is a model good enough to use if it is never finished?" "Do I need a better model if the one I am using works?" We did not answer this question and it is one we must always deal with. Validation of a model usually involves prediction and checking with an independent set of data. What if, as in the case of predicted climate changes, there is no set of data to check it with? Gain from genetic improvement is another example. By the time you have data to prove gains from first generation selections, geneticists are operationally producing third- or fourth generation selections for use. This leads me to suggest that we will desire and need professional estimates for some models. For example, I believe many of the probabilities needed in the silvicultural model presented by Ms. Pearce will always have to be developed this way. By the time we have the experience base for data-supported probabilities for a particular treatment, operational silviculturalists will have modified their treatments due to technology and ideas on how to improve success and reduce costs.

I am also pleased to see the trend of benefits from the forest being modeled by looking at several criteria. Fiber, dollars, employment, wildlife habitat, and others appear to be catching on. This leads me to have some faith that we may move more rapidly into integrated resource management as suggested by Mr. Kiil at the start of the conference. If we do not, we will not be making the decisions that many of our decision support systems are being designed to support.

Before closing, I would like to summarize the conference with an overhead of an impression of the acronyms that overwhelmed me at this conference. My problem now is which acronym should I select to help me decide whether I plant the seedling green side up or down, and which should I select to help me decide what my next research project will be?

CLOSING REMARKS

V.C. Begrand
Saskatchewan Parks, Recreation and Culture
Prince Albert, Saskatchewan

This symposium, being the last in a series, should make us feel really good. I think that we have left the best and most important until the last. I must confess, however, that when I first heard that this last symposium was to be on forest modeling, I thought we had been shortchanged.

After all, in 1987 in Winnipeg, GIS (geographic information systems) was the buzzword of the day. It is interesting that the subject is still very timely in 1989. At that time, talk was about geographically referenced information bases and how to display and manipulate them.

In 1988, the focus was on the important topic of mixedwood management and the need to improve our knowledge base in that area of the boreal forest.

This symposium challenged us to look even further than I ever dreamed to look, in terms of what we in the forestry community will be expected to predict. We were shown how modeling is used in many different resource sectors and how models can be used in the monumental task of integrating resource management alternatives in the future.

This symposium was in my opinion, a smashing success. I measured success in two ways:

1. The cross-section of delegates was exceptionally varied, not only in terms of backgrounds, responsibilities, and employers, but also in terms of where they came from.

2. The speakers selected provided to the delegates information and experiences that were timely, useful, informative, and at times provocative.

Forestry Canada, under the guidance of Dave Kiil at the Northern Forestry Centre, must be acknowledged for their initiative. The support and cooperation from all three prairie provincial governments and the three prairie federal-provincial forest resource development agreements must also be noted.

The moderators deserve to be recognized for their help, not only in keeping the sessions on time but for their handling of each session.

The participating displayers provided that "little extra" to the symposium. Without them this symposium would not have been as interesting.

Of course the organizing committee deserves special recognition for seeing that the symposium was conducted almost flawlessly. Steve Price as symposium coordinator and the following Forestry Canada staff deserve a big thank you: Claire Abma, Kelly Bacon, Gordon Barth, John Mrklas, Bob Newstead, and Stephan Szabo.

I have been advised by a high-ranking official of Forestry Canada that the proceedings of this symposium will be out in record time. That probably means before the end of the payout period of the existing Canada-Saskatchewan development agreement.

In his opening remarks yesterday, Dave Kiil reminded us that the two past symposia prompted significant activities or projects in the region. With the pending expiration of the federal-provincial forest resource development agreements in the prairies, I cannot help but wonder what project or activity this final symposium will prompt during the next few months.

We must be optimistic that collectively we will find a way to continue with the development of forest modeling techniques and strategies. The challenge is ours. Our children's future is at stake.

Thankyou for coming. Have a safe journey home.

SPEAKERS AND PARTICIPANTS

Speakers

Alan Appleby
Saskatchewan Parks, Recreation and Culture
3211 Albert Street
Regina, Saskatchewan
S4S 5W6

Mike Apps
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

James Beck
Forest Science Dep.
University of Alberta
855 General Services Bldg.
Edmonton, Alberta
T6G 2H1

Vic Begrand
Saskatchewan Parks, Recreation and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Jamie Benson
Saskatchewan Parks, Recreation and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Pierre Bernier
Forestry Canada
Laurentian Forestry Centre
C.P. 3800
Ste Foy, Quebec
G1V 4C7

Dave Boulter
Chief Analyst
Econmics Branch
Forestry Canada
Ottawa, Ontario
K1A 1G5

Dave Depta
Weyerhaeuser Co.
Tacoma, WA 98477
USA

Tom Erdle
Dep. Forests, Mines & Energy
P.O. Box 6000
Fredericton, New Brunswick
E3B 5H1

Bob Fessenden
Vice-President
Natural Resources Division
Alberta Research Council
P.O. Box 3800, Stn. F
Edmonton, Alberta
T6H 5X2

John Kansas
Wildlife Habitat Biologist
Beak Associates Consulting Ltd.
250, 2635 - 37 Avenue N.E.
Calgary, Alberta
T1Y 5V7

Dave Kiil
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Dr. Hamish Kimmins
1929 West 44th Avenue
Vancouver, British Columbia
V6M 2E8

Dr. Kurt Klein
Economics Department
University of Lethbridge
Lethbridge, Alberta
T1K 3M4

Bob Lamont
Manitoba Forestry Branch
300, 530 Kenaston Blvd.
Winnipeg, Manitoba
R3N 1Z4

Bryan Lee
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Hugh Lougheed
Information Services Supervisor
Weldwood of Canada Ltd. (Hinton Division)
760 Switzer Drive
Hinton, Alberta
T7V 1V7

Glenn Manning
Chief, Economic Analyst
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia
V8Z 1M5

Colin Maxwell
Minister
Saskatchewan Parks, Recreation
and Culture
Rm. 340, Legislature Bldg.
Regina, Saskatchewan
S4S 0B3

Robert Morton
Silvacom Ltd.
9120 - 37 Avenue
Edmonton, Alberta
T6E 5L4

Reino Pulkki
School of Forestry
Lakehead University
Thunder Bay, Ontario
P7B 5E1

Cindy Pearce
310, 2505 W. 42 Avenue
Vancouver, British Columbia
V6M 2B5

Don Reimer
D.R. Systems Inc.
320, 256 Wallace St.
Nanaimo, British Columbia
V9R 5B5

Ted Robak
University of New Brunswick
Fredericton, New Brunswick
E3B 6C2

Ken Runyon
Forestry Canada
Box 4000
Fredericton, New Brunswick
E3B 5P7

Neil Stevens
14011 - 101 Avenue
Edmonton, Alberta
T5N 0K2

Jan Volney
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Doug Walker
Forest Management Coordinator
Weldwood of Canada Ltd. (Hinton Division)
760 Switzer Drive
Hinton, Alberta
T7V 1V7

Elaine Wheaton
Saskatchewan Research Council
15 Innovation Blvd.
Saskatoon, Saskatchewan
S7N 2X8

Evelyn Wrangler
Director
Timber Management Branch
9th Floor, Bramalea Bldg.
9920 - 108 St.
Edmonton, Alberta
T5K 2M4

Participants

Claire Abma
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Mark Adamson
NorSask Forest Products Inc.
Box 10
Meadow Lake, Saskatchewan
S0M 1V0

Doug Allan
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Stig Anderson
Forestry Canada
Great Lakes Forestry Centre
P.O. Box 490,
Sault Ste. Marie, Ontario
P6A 5M7

Andrea Atkinson
Saskatchwean Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Kelly Bacon
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Hugh Barclay
Forestry Canada
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia
V8Z 1A6

Gord Barth
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Gerry Becker
Manitoba Natural Resources
Forestry Branch
300, 530 Kenaston Blvd
Winnipeg, Manitoba
R3M 1Z4

Jack J. Bell
Sask. Council of Independent Forest
Industries
Box 228
La Ronge, Saskatchewan
S0J 1L0

Imre Bella
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Jerry Bentz
Alberta Forestry, Lands and Wildlife
Land Information Services Division
8845 - 108 Street
Edmonton, Alberta
T5K 2G6

Ron Berezowski
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Don Bernier
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Alphonse Bird
Montreal Lake Band
General Delivery
Montreal, Saskatchewan
S0J 1Y0

Brent Bitten
Terrestrial and Acquatic
Environmental Managers Ltd
Box 2647
Melville, Saskatchewan
S0A 2P0

Lorne Brace
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Gerald Brahniuk
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Dave Brown
Crestbrook Forest Ind.
P.O. Box 1313
Edmonton, Alberta
T5J 2M8

Dan Bulger
Ontario Ministry of Natural Resources
Kirland Lake District
P.O. Box 129
Swastika, Ontario
P0K 1T0

Allan Campbell
Saskatchewan Parks, Recreation
and Culture, Forestry Branch
3211 Albert Street
Regina, Saskatchewan
S4S 5W6

Dale Campbell
Camsal
Box 2049
Meadow Lake, Saskatchewan
S0M 1V0

Nello Cataldo
Forestry Canada
Manitoba District Office
104, 180 Main Street
Winnipeg, Manitoba
R3C 1A6

Terry Chow
Shuswap Nation Tribal Council
345 Yellowhead Highway
Kamloops, British Columbia
V2H 1H1

Chris Cieszewski
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Peter Clarkson
Abitibi-Price Inc.
P.O. Box 10
Pine Falls, Manitoba
R0E 1M0

Steve Clautice
Alaska Division of Forestry
3600 Airport Way
Fairbanks, AK 99709
USA

Ian Corns
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Percy A. Crosthwaite
Prairie Industrial Chemicals Inc.
P.O. Box 628
Davidson, Saskatchewan
S0A 1W0

Sean Curry
Weldwood of Canada Ltd.
(Hinton Division)
760 Switzer Drive
Hinton, Alberta
T7V 1V7

Joe De Franceschi
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Bill DeGroot
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Henry J. Desjarlais
Saskatchewan Parks, Recreation
and Culture
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Bob Durocher
Abitibi-Price Inc.
P.O. Box 10
Pine Falls, Manitoba
R0E 1M0

Dwayne Dye
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Garth Edwards
Consultant
Monitech Ltd
35 Mason Crescent
Saskatoon, Saskatchewan
S7H 3B8

Ivor Edwards
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Janice Edwards
Petawawa National Forestry
Institute
Box 2000
Chalk River, Ontario
K0J 1J0

Ben Ellert
Department of Soil Science
University of Saskatchewan
Saskatoon, Saskatchewan
S7N 0W0

Ron Eytcheson
Silviba Services Ltd.
P.O. Box 1643
Prince Albert, Saskatchewan
S6V 5T2

Ray Fautley
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

James Fraser
Abitibi-Price Inc.
P.O. Box 10
Pine Falls, Manitoba
R0E 1M0

Gord Frey
Saskatchewan Parks, Recreation
and Culture
Box 3003
Prince Albert, Saskatchewan
S6V 6K9

Alex Gardner
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Dr. David A. Gauthier
Department of Geography
University of Regina
Regina, Saskatchewan
S4S 0A2

Keith Gorham
Saskatchewan Parks, Recreation
and Culture, Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Harjit Grewal
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Fern Gruszka
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Ron Hall
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Carl Halland
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Dave Hanline
Saskatchewan Parks, Recreation
and Culture, Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

David Harman
NorSask Forest Products Inc.
Box 10
Meadow Lake, Saskatchewan
S0M 1V0

Tom Hartnett
Smokey Lake Tree Planters Ltd.
Box 577
Big River, Saskatchewan
S0J 0E0

Edward Henderson
Montreal Lake Bank
General Delivery
Montreal Lake, Saskatchewan
S0J 1Y0

Steve Hyde
Saskatchewan Parks, Recreation
and Culture
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Jim Johnston
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Vince Keenan
Abitibi-Price Inc.
P.O. Box 10
Pine Falls, Manitoba
R0E 1M0

Gene Kimbley
Montreal Lake Band
General Delivery
Montreal Lake, Saskatchewan
S0J 1Y0

Walter Koch
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003,
Prince Albert, Saskatchewan
S6V 6G1

Edward H. Kowal
Saskatchewan Parks, Recreation
and Culture
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Andre Kruger
Forestry Canada
Northern Forestry Canada
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Dieter Kuhnke
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Werner Kurz
Forest Sciences Department
University of British Columbia
2357 Main Mall
Vancouver, British Columbia
V6T 1W5

John T. Kus
Ontario Ministry of Natural Resources
258 Quuen Street East
Sault Ste. Marie, Ontario
P6A 5N5

Paul Kutz
Simpson Timber Co.
(Saskatchewan) Ltd.
Box 760
Hudson Bay, Saskatchewan
S0E 0Y0

Janet Lane
Weyerhaeuser Canada
P.O. Box 1720
Prince Albert, Saskatchewan
S6V 5T3

Bill Latocha
Dep. Natural Resources
Division of Forestry
SR Box 7-005
Anchorage, AK
USA

Dave Lindenas
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Murray Little
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Phil Loseth
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Stan Lux
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Dan MacIsaac
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Surj Malhotra
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

John McQueen
Forestry Canada
Manitoba District Office
104, 180 Main Street
Winnipeg, Manitoba
R3C 1A6

Darcy Mitchel
General Delivery
Prince Albert, Saskatchewan
S6V 5P7

Walter Moore
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Tom Mord
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

John Mrklas
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Stan Navratil
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Duncon Newman
NewForest Resources Inc.
1003 1st Ave. W.
Prince Albert, Saskatchewan
S6V 4Y3

Michael Newman
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Bob Newstead
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Thomas Niemann
Ministry of Forests
1450 Government Street
Victoria, British Columbia
V8W 3E7

Frank Oberle
Sauze Forestry Service
Building A, 104,
5904 - 50 Street
Leduc, Alberta
T9E 6J5

Francis Olson
Box 1078
Drumheller, Alberta
T0J 0Y0

Michelle Olson
Box 1078
Drumheller, Alberta
T0J 0Y0

Bill Ondro
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Ed Packee
University of Alaska, Fairbanks
Fairbanks, AK 99775
USA

Jim Page
State of Alaska
Division of Forestry
P.O. 520455
Big Lake, AK 99652
USA

Madan M. Pandila
Saskatchewan Parks, Recreation
and Culture
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Del Parker
Ontario Ministry of Natural Resources
119 Larch Street
Sudbury, Ontario
P3E 5P9

Bijan Payandeh
Forestry Canada
Great Lakes Forestry Centre
P.O. Box 490, 1219 Street East
Sault Ste. Marie, Ontario
P6A 5M7

Margaret Penner
Forestry Canada
Petawawa National Forestry Institute
Chalk River, Ontario
K0J 1J0

Wayne Pepper
Saskatchewan Parks, Recreation
and Culture
Integrated Resource Policy
Unit, 3211 Albert Street
Regina, Saskatchewan
S4S 5W6

Glenn Peterson
Manitoba Natural Resources
Forestry Branch
300, 530 Kenaston Blvd
Winnipeg, Manitoba
R3M 1Z4

John Powell
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Steve Price
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Michael Rain
Beak Consulting
1070 - 8th Avenue
Regina, Saskatchewan
S4R 1C9

Jim Richardson
Forestry Canada
Ottawa, Ontario
K1A 1G5

Roger Roberge
Forestry Canada
Ottawa, Ontario
K1A 1G5

Jacques Robert
Forêts Canada
180 rue des Gouverneurs
3iéme étage
Rimouski, Quebec
G5C 8G1

Lorenzo Rugo
Forestry Canada
Ottawa, Ontario
K1A 1G5

Jim Saunderson
Western Diversification
1500 Canada Place
9700 Jasper Avenue
Edmonton, Alberta
T5J 4H7

Doug Schindler
(no address)

Daryll Sewell
Industrial Science and Technology
6th Floor
105, 26 Street East
Saskatoon, Saskatchewan
S7K 0B3

Art Shortreid
Forestry Canada
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia
V8Z 1A6

Derek Sidders
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Teja Singh
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Art Skibinsky
Beak Associates
1070 - 8th Avenue
Regina, Saskatchewan
S4R 1C9

Mike Slivitsky
Manitoba Natural Resources
Forestry Branch
300, 530 Kenaston Blvd
Winnipeg, Manitoba
R3M 1Z4

Barton Smith
Barton Smith Forest
Technical Services
Saskatoon, Saskatchewan

Richard M. Smith
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

John Spence
University of Alberta
Department of Entomology
Edmonton, Alberta
T6G 2E3

Larry Stanley
Saskatchewan Parks, Recreation
and Culture, Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Bob Stewart
Terrestrial and Acquatic
Environmental Managers Ltd
Box 2647
Melville, Saskatchewan
S0A 2P0

Bob Stoddart
Saskatchewan Parks, Recreation
and Culture, Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Stefan Szabo
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

James A. Taylor
Department of Forestry (NFLD)
P.O. Box 2006, Herald Building
Cornerbrook, Newfoundland
A2H 6J8

John Thompson
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Rod Thompson
Saskatchewan Parks, Recreation
and Culture
Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Jeffrey Thorpe
Ecological Consultant
194 Gladmer Park
Saskatoon, Saskatchewan
S7J 2X3

Dick Tindall
Tindall Enterprises
6821 Sherwood Avenue
Anchorage, AK 99504
USA

Steve Titus
Department of Forest Science
University of Alberta
Edmonton, Alberta
T6G 2H1

Peter Todd
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Joe Van Dyk
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Dale Vizina
Saskatchewan Forest Products
550, 1st Ave East
Prince Albert, Saskatchewan
S6V 2A5

Bruce Walter
Saskatchewan Parks, Recreation
and Culture, Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Russ Wells
Pedo-Ecological Consultants
10845 - 32A Avenue
Edmonton, Alberta
T6J 3B8

Bill White
Forestry Canada
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia
V8Z 1M5

Lorie Wiesner
Forestry Canada
Saskatchewan District Office
101, 15 Street East
Prince Albert, Saskatchewan
S6V 1G1

Tim Williamson
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Floyd Wilson
Saskatchewan Parks, Recreation
and Culture, Forestry Branch
Box 3003
Prince Albert, Saskatchewan
S6V 6G1

Milton Wurts
Terrestrial and Acquatic
Environmental Managers Ltd
Box 2647
Melville, Saskatchewan
S0A 2P0

Dick Yang
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Voyteck Zakrzewski
Forestry Canada
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5