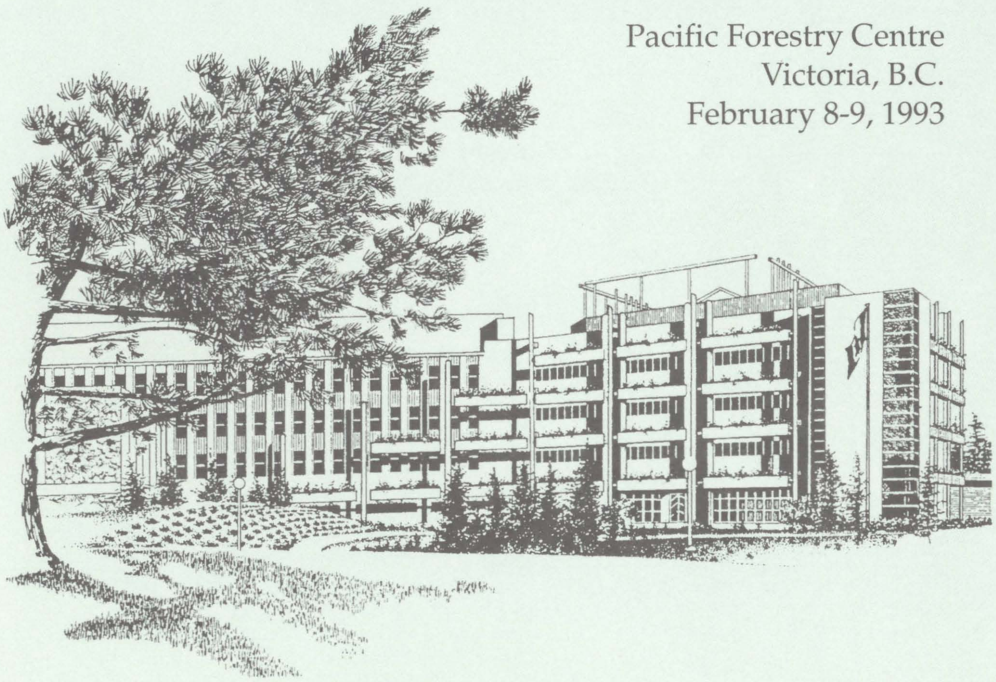
FORESTRY CANADA MODELLING WORKING GROUP

Proceedings of the Seventh Annual Meeting and Workshop

Pacific Forestry Centre
Victoria, B.C.
February 8-9, 1993



Compiled by G.M. Bonnor

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FOREWORD

The Forestry Canada Modelling Working Group serves as a forum for scientists to discuss and exchange information on their modelling research: methodologies, progress, and problems. Most modelling relates to growth and yield but modelling in other fields such as insects and diseases, hydrology, fire, climate and carbon cycling is also included.

A recent trend in these annual meetings is to invite speakers from outside Forestry Canada to attend and talk about their research, to give ForCan scientists an appreciation of the type and magnitude of research done in the Region. This practice was continued here: three of the nine presentations were made by staff from the Ministry of Forest and the University of British Columbia.

On the morning of the first day, four papers were presented. The afternoon was devoted to three model demonstrations, including the newly developed STIM growth model. The second day opened with the Working Group Business Meeting, which was followed by presentation of the final two papers. The remainder of the day was devoted to a field trip to the Shawnigan Lake Research Installation, to look at the effect on growth 20 years after thinning and fertilization in a Douglas-fir stand.

The meeting was a success in terms of technical presentations as well as attendance: 39 foresters attended one or both days.

G.M. Bonnor
Chairman

AGENDA

Monday, February 8

9:30-10:00	- Coffee
10:00-10:15	- Opening and Welcome
10:15-12:00	- Technical Papers - J. Vivian (MOF): Growth modelling in the Inventory Branch. - K. Mitchell (MOF): Growth modelling in the Research Branch. - A. Thomson (ForCan): Remote sensing and forest modelling. - C-H. Ung (ForCan): Growth and branchiness of Picea mariana.
12:00-13:00	- Lunch
13:00-16:00	- Model Demonstrations - M. Bonnor et al. (ForCan): The STIM growth model - A. Thomson (ForCan): A variable density lodgepole pine model for mountain pine beetle impact evaluation (Coffee at 15:00) - P. Newton (ForCan): Stand density management models for managed black spruce stands

Tuesday, February 9

8:30-10:00	- ForCan Modelling Working Group - Business Session - Report from Establishments
10:00-10:30	- Coffee
10:30-11:30	- Technical Papers (cont'd) D.T. Price (ForCan): Use of a forest ecosystem level model to investigate responses of boreal landscape productivity to climate V. LeMay (UBC): Tree growth based on projection of taper models over time
11:30	- Departure for Shawnigan Lake
12:30-13:30	- Lunch
13:30-15:00	- Field Trip to Shawnigan Lake Research Installation
15:00-16:00	- Return to Victoria

Technical Papers

OVERVIEW OF GROWTH AND YIELD MODELLING WITHIN THE INVENTORY PROGRAM INVENTORY BRANCH MINISTRY OF FORESTS

by J. Vivian
Inventory Branch, Ministry of Forests, Victoria, B.C.

GROWTH AND YIELD PROGRAM OVERVIEW

The Inventory Branch, Ministry of Forests maintains an operational Growth and Yield Program as one of its main function areas. The program is comprised of a staff of 13 Full Time Equivalents (F.T.Es.) with an annual operating budget of about 3 million dollars. The main functions of the program are:

1. establish and maintain a series of permanent sample plots (PSPs) on a provincial basis suitable for the development, calibration and validation of growth and models;
2. maintain a corporate database of temporary sample plots (TSPs), PSPs and volume and decay data;
3. develop loss factors through sampling and establishing relationships between species and levels of decay;
4. calibrate and implement tree taper equations;
5. develop, implement and support yield functions suitable for the update and projection of the provincial inventory;
6. acquire, calibrate, operationally implement and maintain a variety of growth and yield models for the prediction of natural stands; and
7. provide an audit on growth and yield methodologies utilized by the private sector.

Research into growth and yield is maintained by the Forest Productivity and Decision Support (FPDS) Section of Research Branch. This group is responsible for developing managed stand yield curves (eg. Tree and Stand Simulator—TASS) as well as site index curves, investigations into site productivity and species dynamics. Much of the PSP data collected by Inventory Branch is used by FPDS to validate TASS and other models. Further cooperation exists in the area of site productivity, whereby Inventory Branch supplies data for site curve construction and validation.

The Inventory Branch operational Growth and Yield Section consists of four groups:

1. Growth Sampling;
2. Growth and Yield Prediction;
3. Volume & Decay; and
4. GIS/Database.

The Growth Sampling Group maintains a PSP program consisting of over 7,000 PSPs throughout the province including both Tree Farm License (TFL) and Timber Supply Area (TSA) administration. A variety of sample programs are maintained, but by far the largest effort is put into the Growth Natural Program. Approximately 400 PSPs are established annually to matrices developed cooperatively with the Forest Productivity Councils of B.C.

The Growth and Yield Prediction Group is currently completing the first phase of a Variable Density Yield Prediction (VDYP) System for release in April, 1993. Other projects include building a growth-based version of VDYP and operationally implementing the U.S. stand model "Prognosis". The Volume and Decay Group samples for decay by species and risk group throughout the province. The data are used to develop loss factors for application in both sample compilation as well as stumpage assessment. Single tree volume data are also collected for calibrating taper functions.

The GIS/Database Group provides technical support for all programs by maintaining databases and software systems at both the VAX and PC level. Current efforts are aimed at developing a corporate relational database for all ministry growth and yield sample data.

Budgets for this program have increased four-fold since 1988, largely due to the efforts of the Forest Productivity Councils of B.C. who have considerably raised the profile of growth and yield. Over half of the budget is directed to the PSP Program that has been decentralized to the six forest regions. Each region has a Growth and Yield Forester who is responsible for the establishment, remeasurement and ecological assessment of all PSPs.

EVOLUTION OF YIELD PREDICTION IN THE INVENTORY PROGRAM

Growth and yield modelling activities have, until recently, been directed to updating the provincial inventories. The provincial inventory is composed of 7,027 map files. Of these, 6600 cover TSAs, 170 are totally within TFLs, 170 are parks and the rest cover private land. Each map (approx. 15,000 hectares) contains anywhere from 200 (north) to over 1500 polygons (southeastern B.C). It is estimated that there are over 3,500,000 polygons in B.C. for which the volume, quadratic mean diameter and height are derived from yield functions. Reinventories are planned on a 10-year cycle whereby new forest cover information is brought into the system and updated on a two-year cycle.

There has been a considerable evolution in the methods used to assign volumes and other stand parameters to the provincial inventory. From the 1950's to 1985, mature species volumes were assigned from Average Volume Lines (AVLs) which were numerical means of stratified random samples grouped by age, site class and stocking class for each of the 42 Inventory Type Groups. Over 50,000 temporary sample plots from surveys dating back to 1953 were utilized. Volume/Age curve construction appeared in the 1960's. Mean volume and diameter values for each ten-year age class were manually derived and initially hand-fitted with a French curve over data grouped by anamorphic site classes. A further refinement fitted a fifth-degree polynomial function through the sample means and heralded the application of mathematical functions for yield estimation by Inventory Branch.

During the 1970's, the Chapman-Richards' generalized growth function replaced the polynomial formulation. This approach, now referred to as VACs & DACs (volume/diameter over age curves) was largely intended for use in timber forecasting, not for inventory update application. As with the earlier polynomial class groupings, volume and diameter were regressed against age using the Marquardt non-linear algorithm on IBM main-frame systems. The VAC system was later modified to become the first VDYP system, introducing site index and crown closure as independent variables. As polygon crown closure was not available across the province, this system was never operationally implemented. This system has been documented in Inventory Reports 2 and 3.

With the failure to implement VDYP there was an immediate need for a yield system that could fill the requirements for inventory update and yield projections in the new timber supply analyses.In 1982, joint collaboration between Inventory and Research Branches resulted in the Site Index System (formerly referred to as the "Ek-Payandeh/ Volume Ratio System). The Site Index System regressed age and site index against volume for the 7.5 cm+ level of utilization. A volume ratio formula was developed for higher levels of utilization, eg. 12.5 cm+. Diameter prediction was supplied using a modified Chapman-Richards' equation. Intended as an interim model, the Site Index System has been used extensively up to the present and is documented in "Growth and Yield Prediction Systems, T.M. Thomson, Feb. 1991, ISSN 0843-6452", available from Inventory Branch.

The Site Index System was hurriedly designed and implemented with little testing. Applied as both a point yield estimator for inventory update and as a yield projector for the timber supply analyses, numerous problems and inconsistencies were quickly uncovered. Unfortunately, these were remedied through adjustments, rather than re-engineering the architecture. These limitations were finally addressed in the late 1980's through the design of a revised VDYP system. Designed primarily as an empirical yield function, VDYP also includes a basal area driven model providing growth-based predictions. With over three years of development, VDYP has been thoroughly tested both internally and by a number of growth and yield agencies. VDYP links to the inventory through the classification system. At this point in time, no other readily available yield model offers this functionality.

VDYP is scheduled for release in April, 1993 and will replace all former systems for natural stand estimation and projection. The basal area driven version is currently being calibrated and will be released after further testing.

Inventory Branch is currently investigating other models for specialized uses. The U.S. stand model "Prognosis" is currently being adapted to B.C. conditions for interior uneven-stands and will be operationally tested in the Nelson Forest Region in 1993. Similarly, Forestry Canada's "STIM" growth model will be tested and considered for implementation.

GROWTH AND YIELD MODEL REQUIREMENTS

Given the specifications of the current inventory, a model for inventory update must accommodate the following criteria:

- consistency with the current inventory classification system for species composition, age, height and crown closure;
- simple in design, robust and fitted for all species and species mixes in the province; designed for single and batch processing;
- calibration on both temporary and connected plot data;
- prediction for both immature and mature age classes;
- account for decay, waste and breakage losses;
- process a map label in a few seconds; and
- integrate with GIS and work under DOS, UNIX and VMS environments.

OTHER CONSIDERATIONS FOR INVENTORY UPDATE MODELLING

Expectations on the reliability of growth and yield models for inventory update are often in excess of what can realistically be developed. For example, in the fitting of the VDYP model, developers have relied heavily on the use of temporary (inventory) sample plots as other suitable data were not available. Portions of this large, historic database date back to the early 1950's and may not portray the range and proportion of stand conditions that exist today. Further to this, the crown closure variable has been subjectively estimated from aerial photographs and reflects the bias of the interpreter. Subjecting this mixture of data and interpretation to advanced statistical fitting procedures with expectations for stand specific results is not realistic. At best, results from the new VDYP model should reflect "average" conditions for groups of similar stands on a large, geographical basis. Models such as VDYP that are projected on site curves are also vulnerable to incorrect initial estimates of site productivity, hence the model requires reliable inventory estimates to produce valid predictions.

It should be emphasized that VDYP is an empirical yield model designed primarily for inventory update, not for silvicultural or timber supply applications. Given the immediate need for yield projections in the three-year Timber Supply Review, VDYP was selected by Integrated Resources Branch as being the only readily available model compatible with the provincial inventory. To provide some assurance that VDYP could be used for longer-term projections, the following procedures are incorporated:

immature and mature samples are fitted separately (if necessary) and resulting projections are splined together to provide a smooth, continuous flow of yield;

height projections supplied from site index curves are constrained to reflect maximums found in the provincial inventory;

model projections for immature stands are checked against connected PSP data; and

waste and breakage factors as well as stocking adjustments are applied as a continuous function of age.

A basal area (ground-based) version of VDYP has been developed and will be used, along with other suitable models, to ensure yield projections track demonstrated growth trends yet reflect operational conditions. The use of Forestry Canada's STIM Model will be integrated into this process.

Further work on VDYP has been identified and will become available through twice-yearly scheduled releases. Emphasis will be placed in the areas of species dynamics, localization, and re-fitting models on data stratified on a biogeoclimatic ecosystem classification (BEC) basis. Reductions for decay and waste will be applied as stand-level operational adjustment factors. Finally, and most importantly, inventory update models will evolve with advances in forest inventory procedures.

REMOTE SENSING AND FOREST MODELLING

by Alan J. Thomson
Pacific Forestry Centre, Victoria

The Advanced Forest Technologies Program at PFC is a new program, headed by Dr. D. Goodenough from CCRS. The major goals of the program are

- Extracting forest information from remotely sensed data
- Combining GIS and Remote Sensing with Artificial Intelligence
- Developing decision support systems involving ecosystem,environmental and forest models which integrate with remote sensing and GIS
- Developing multimedia products for decision support

The major project within the program is development of a System of Experts for Intelligent Data Management (SEIDAM). SEIDAM is a project of the NASA Applied Information Systems Research Program (Goodenough et al. 1993). Of 350 proposals submitted to the program, only 22 were selected, and of these, there was only 1 non-US proposal funded (SEIDAM).

SEIDAM is aimed at the data management problems of the next decade, when more than 60 sensors will be generating in excess of a terrabyte of data per day. SEIDAM features queries which will trigger expert systems. The expert systems will determine the appropriate data and processing. Processing methods can include image analysis, models and GIS. We will be using remote sensing data from 8 satellite sources and six aircraft sources, and testing the system on three sites in B.C., each approximately 20km x 20km. The three sites are the Greater Victoria Watershed, Tofino Creek (in Clayoquot Sound), and Parson in the Rockies.

Major Cooperators in the project include NASA, CCRS, ISTC Strategic Technologies Branch, BCMF Inventory Branch, BCMELP Surveys and Resource Mapping Branch, and the EEC Joint Research Centre Microwave Signatures Laboratory.

REMOTE SENSING BASICS

There are two types of sensor, optical and microwave (radar). Different sensors have different bandwidths and numbers of bands. Bandwith is the range of wavelengths covered by a channel in the sensor.The area of ground represented by a pixel in the image depends on the sensor and the altitude of the platform. Correlations are established between combinations of bands and features measured on the ground.

New sensors can measure foliage chemistry, including chlorophyll. Figure 1 illustrates the chemical absorption spectra of chlorophyll a and b. The peaks at 646 and 662 nm are used. As the peaks are only 16 nm apart, it is evident that a sensor with a narrow bandwidth is required to separate chlorophyll a and b. Possible sensors are CASI (Compact Airborne Spectrographic Imager) with a 1.8 nm bandwidth and AVIRIS (Airborne Visible/ Infrared Imaging Spectrometer with a 10 nm bandwidth. Our interest in chlorophyll will be described later.

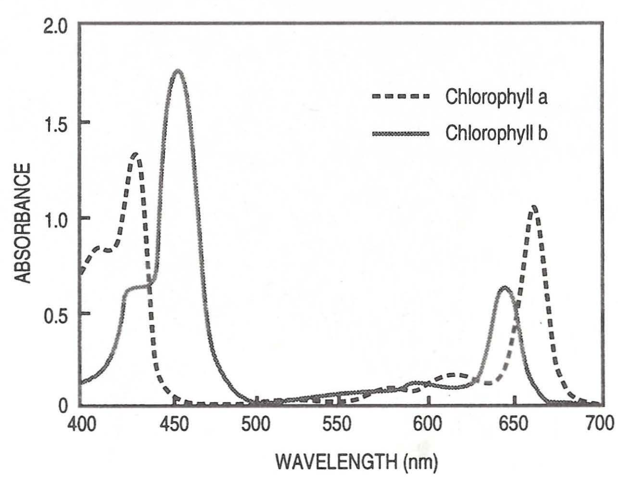

Figure 1.
The absorption spectrum of chlorophyll a and b.

REMOTE SENSING STUDIES RELEVANT TO FOREST MODELLING

Remote sensing estimates of forest features can be used either as inputs to models, or as checks against model output. Features of interest are illustrated by a brief literature review.

Remote sensing has now been used for determining leaf area index (LAI) (Gong et al. 1992, Peterson et al. 1987) and crown closure (Archibald 1987) for some time. Running et al. (1989) estimated annual evapotranspiration and net photosynthesis by coupling LAI from satellite data with an ecosystem simulation. Photosynthesis and transpiration were also studied by Sellers et al. (1992). and Myneni et al. (1992).

More recent sensors and methods have been used to study forest structure and canopy chemistry. For example, Cohen and Spies (1991) correlated forest structural attributes such as mean and s.d. of dbh and crown diameter, canopy diversity, basal area and tree density with SPOT HRV and LANDSAT TM data. Ambrosia et al. (1992) also measured stand structure, as well as forest species.

Peterson et al. (1988) measured canopy nitrogen and lignin, and discussed the potential of the approach for productivity, decomposition and nutrient turnover rates. Wessman et al. (1989) also measured nitrogen and lignin, and actually produced a map showing the spatial distribution of annual nitrogen mineralization rates.

Forest biomass has been measured by Dobson et al. (1992) and Moulton et al. (1990). Other uses include determination of forest site fertility (Tomppo 1992) and spruce budworm damage (Leckie et al. 1992).

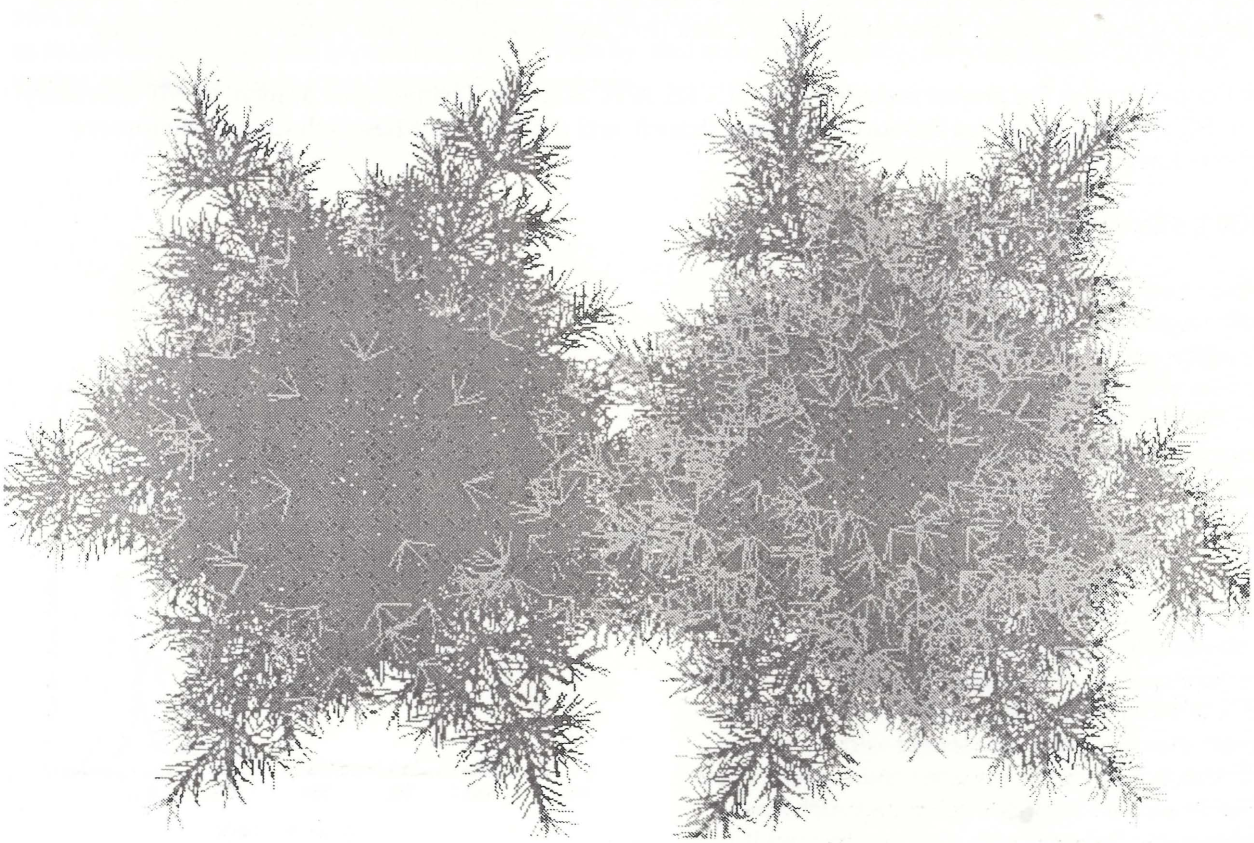

Figure 2. Trees showing new shoots at intermediate stages of growth (33% and 66% of the old shoot length).

TREES++

We have developed an object-oriented graphics program (TREES++), written in C++, to simulate the effects of stand structure and changing canopy chemistry on the characteristics of a pixel as perceived by a sensor. The system can also be used to display damage or defoliation.

We are interested in being able to detect bud flush in conifers using remote sensing. Preliminary tests suggest that the chlorophyll a/b ratio is different in old and new foliage. New foliage, when fully extended, is only about 35% of the total foliage complement of the tree. However, the new foliage lies on the outside of the crown and may mask the old foliage.Figure 2 illustrates a tree crown with the new shoots 33% and 66% extended. With full extension, the new foliage was found to effectively mask the old foliage when viewed from above.

SUMMARY

Recent advances in remote sensing permit measurement of stand structure and canopy chemistry, photosynthesis and transpiration, as well as the more traditional LAI and crown closure. The Advanced Forest Technologies program at PFC is involved in a major international forestry remote sensing project, SEIDAM, which will use such approaches to answer forest level queries. An object-oriented graphics program, TREES++, under development at PFC, will provide the linkage between the forest and the remote sensing.

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GROWTH AND BRANCHINESS OF PICEA MARIANA (MILL.) BSP

by Chhun-Huor Ung
Forestry Canada, Quebec Region

ABSTRACT

The simultaneous growth and wood quality modeling constitutes the extension of the present models concentrated on the production function of the forest stands. This extension allows the tree crown to play important roles in the growth process.

On one hand, the crown with its biomass and leaf area acts as the mover of growth. On the other hand, its development's mark, i.e. knots, concern wood technologists.

It is within this context that the communication presents the preliminary results of a study on the growth and branchiness of black spruce regenerated by seeding and layering in the Laurentian Wildlife Reserve (Quebec).

USE OF A FOREST ECOSYSTEM-LEVEL-MODEL TO INVESTIGATE RESPONSES OF BOREAL LANDSCAPE PRODUCTIVITY TO CLIMATE

by D T Price & M J Apps
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ABSTRACT

Anticipated changes in global climate due to increasing concentrations of atmospheric greenhouse gases may have significant socio-economic impacts on Canadian forest resources, and on their evident function as terrestrial carbon sinks of global significance. Assessments of these possible impacts will be best achieved through use of national-scale integrating models of the Canadian forest land base. Important climate-sensitive processes occur at both large scales (ecosystem disturbances) and fine scales (growth, respiration and decomposition); it is essential to consider both levels of organization if an integrating model is to assess consequences of climate change correctly. This paper outlines the ongoing development of an integrating carbon budget model of the Canadian forest sector, which will accept metadata generated by process models of higher resolution (spatial and temporal). An approach to sampling the landscape using a modified forest ecosystem model is presented as a means of scaling the output from small scale models up to the large scale.

INTRODUCTION

The recently developed Phase 1 Carbon Budget Model of the Canadian Forest Sector (CBM-CFS1) (Apps and Kurz 1991; Apps et al. 1991; Kurz et al. 1991, 1992), produced a Canada-wide assessment of the forest sector carbon (C) budget for a single reference year, 1986. After dividing the country into 42 spatial units based on ecological classification (Ecoregions Working Group 1989) and provincial administrative boundaries, the yearly C budget was derived from compilations of available data on the distribution and dynamics of biomass and soil carbon, disturbance statistics, and the fate of forest products. This analysis revealed that although the Canadian forest sector as a whole was a small net-sink for atmospheric carbon, it could be very sensitive to changes in climate-related events, such as an increase in forest fires (Kurz et al. 1992).

A newer version of the model, CBM-CFS2, is now being used to investigate the longer-term sensitivity of the national forest C budget to changes in growth rates, disturbance regimes and other ecosystem processes, such as those which may result from changes in management and/or climate (Kurz and Apps 1992). In CBM-CFS2, large-scale responses to environmental conditions are proscribed rather than simulated, to allow possible consequences for the C budget to be investigated; no attempt is made to simulate the detailed effects of changes in climate and management on ecosystem structure and function. It is now widely recognized however, that the key processes influencing vegetation productivity and distribution are generally nonlinear and of ten highly sensitive to changes in small-scale conditions. Furthermore, many researchers have suggested that vegetation zones of the northern hemisphere will migrate northward in response to climate warming (Zoltai 1988; Rizzo and Wiken 1989; Zoltai et al. 1991; Prentice et al. 1992a), affecting both the area and net productivity of each ecoclimatic region, and hence the large-scale C budget. CBM-CFS2 does not presently consider changes in the distribution of recognized biomes (Kurz and Apps 1992). In this paper, an approach is described for including forest ecosystem-level response models within the prognostic CBM-CFS framework.

OBJECTIVES

Resource managers and policy makers are increasingly expected to consider the potential impacts of climate, management and other factors influencing the productivity of Canada's forests. This almost certainly requires predictive models based on valid simulations of the processes affecting the carbon dynamics of forests and other ecosystems. The ongoing work briefly described here is aimed at parameterizing response surfaces generated by ecosystem process sub-models for use as input data (metadata) for the CBM-CFS. This approach should allow the development of a means of scaling mechanistic representations of key ecological and ecophysiological processes operating at the stand level, including primary production, disturbances, succession, soil carbon dynamics, and atmospheric exchanges, to the spatially and temporally aggregated information required for national forest sector C budget analysis. The objective is to facilitate scenario analyses (Apps and MacIsaac 1990) of the possible responses of Canada's forest C budget to anticipated environmental and managerial changes.

RATIONALE

The world's most extensive forest biome is the boreal forest.In Canada, boreal forest covers approximately 43% of forested land area, and is estimated to harbour 40% of the total inventory of biospheric carbon.Subarctic ecosystems cover about another 20% of Canada's forested area, and although data are scarce, these appear to contain about 35% of total carbon (Apps et al. 1992).In recent years, international attention has been increasingly focused on the northern circumpolar forested regions as possible terrestrial carbon sinks of global importance (e.g. Tans et al. 1990; Apps et al. 1993).

Major research projects have since been initiated to increase understanding of the processes occurring within these ecosystems, including the BOReal Ecosystem Atmosphere Study, BOREAS (BOREAS Science Steering Committee 1990) and the Northern BIosphere Observation and Modelling Experiment (NBIOME, Apps 1993).

As a contribution to both projects, Forestry Canada has initiated a boreal forest transect case study (BFTCS), which will extend the two sites to be studied under BOREAS to include the northern and southern limits of the Canadian boreal forest.The transect covers a distance of approximately 1000 km along a northeast-southwest climatic gradient, (from Batoche in Saskatchewan to Gillam in Manitoba) and will form the basis of an extensive, integrated study of boreal forest processes.Using the BFTCS as a source of data for development and testing, the CBM-CFS framework will be used to incorporate and constrain a suite of smaller scale sub-models which can be tested against the field measurements from which past and present C budget assessments are derived. Once satisfactory agreement has been achieved, the integrated model structure will be used to explore future responses of regional and national forest resources to anticipated changes in climate.

MODELLING APPROACH

Such a challenging task will necessarily involve a strong dependence on the scientific validity of the scaling approach adopted.Two major levels of scaling will be built into the nested suite of models.Simulations of fine-scale processes such as net photosynthesis, evapotranspiration and soil decomposition, will be used to develop species-level response surfaces, which will then be used as metadata for the driving functions of various appropriate ecosystem-level competition models.In turn, the output from these larger scale models will be used as metadata to drive the large-scale C budget model. Changes in vegetation distribution in response to changes in the environment may also be predictable using this approach. The overall concept is illustrated as a flow-chart in Figure 1. Two metamodels are required, operating at two levels of aggregation. Metamodel I will collate small-scale processes at the stand/forest scale, while MII will operate at the regional/biome scale, generating input data for the CBM-CFS.

Assuming good information about the carbon storage and transfer processes within an identifiable "homogeneous" area can be obtained, reasonably accurate estimates of the C budget for each such area should be possible. It then becomes a relatively simple matter to sum the estimates for the entire region of interest, but only so long as there are no significant interactions among these homogeneous areas, (e.g. disturbances and seed dispersal). Vegetation biomass and growth rates, for which information can be obtained from forest sample plots, are important components in deriving an areal C budget. Ecophysiological relationships can also be determined between the climatic variables recorded at a range of different sites, and individual species'

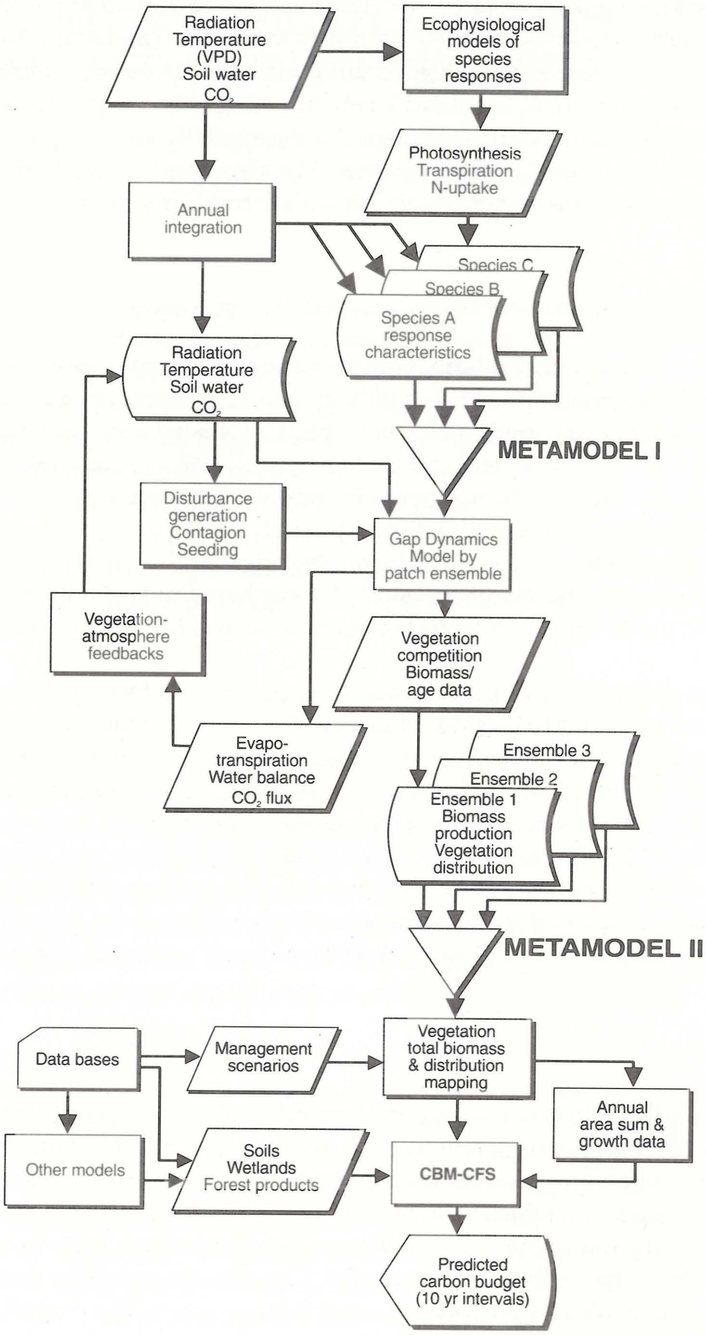

Figure 1. Conceptual flow-chart showing proposed modeling approach for a prognostic carbon budget model of the Canadian forest sector. The top section (above the triangle representing Metamodel I), deals with species-level ecophysiological functions. These converge into a data base of metadata for input into the middle section, (between the two triangles), which deals with stand level functions and effects on ecosystem structure (distribution and composition of stand types simulated by a gap model).

The term "ensemble" is explained in the text. Note that climatic forcing is considered an important factor affecting disturbances, while vegetation feedbacks, (exchanges of CO_2 and water vapor) are also represented. The bottom section, below the triangle representing Metamodel II, integrates ecosystem process simulations, and other sources of data used by the CBM-CFS, to estimate the large-scale carbon budget.

responses (i.e. rates of photosynthesis, respiration, transpiration and nutrient uptake) measured at those sites. BOREAS will provide this kind of information, for a few intensively studied sites, while BFTCS should extend the applicability of the derived relationships to a much larger range of conditions. The objective is to develop functional relationships based on data collected at high temporal and spatial resolution (the response surfaces), for appliction in a much larger scale model, operating over much longer time steps. For example, the relationship of net photosynthesis rate to environmental variation observed over periods of the order of minutes to days, will be used to estimate annual trajectories of net biomass accumulation, based on monthly or even annual climate records. This is an undeniably difficult task, and in the short term it will probably be necessary to make many simplifying (and possibly incorrect) assumptions. This collection of species-specific ecophysiological response functions, based on real data obtained from BFTCS studies, BOREAS or the literature where possible, will form the basis of Metamodel I, which will be used to parameterize the driving functions for the ecosystem-level simulations.

Currently, forest gap phase dynamics (or "gap") models are being explored as the means of simulating boreal ecosystem dynamics, mainly because they are commonly reported in the literature and as a class, evidently work well, though with recognised limitations. The original gap models were developed for temperate and tropical forests where a successional cycle normally occurs within the climax community (Botkin et al. 1972; Shugart 1984; Solomon 1986). Boreal forest succession is not generally considered to be the result of a gap phase replacement process; rather it is normally controlled by periodic disturbances such as fires. Furthermore, regeneration of shade-intolerant pioneer species is disturbance frequency-dependent, leading to some suggestions that boreal climax species such as jack pine and black spruce may even be adapted to encourage disturbance by fire (see Heinselman 1981).

Nevertheless, some researchers have exploited the gap model's representation of spatially aggregated dynamics and introduced other assumptions which allowreasonable success in simulating observed boreal forest structural and functional development (e.g. Bonan 1989, 1991, 1992; Prentice and Leemans 1990; Prentice et al. 1992b).

In most gap models, the forest is assumed to exist under spatially uniform conditions of site productivity and climate, and is represented by a large number of small sample areas, termed "plots", or "patches", which are traditionally considered independent of all other like patches in the forest. Each patch supports randomized stand development and succession, through simulated regeneration, growth, competition and mortality of individual trees, though the ecophysiological processes for each tree are generally based on statistically-derived growth equations, which cannot be reliably extended outside the domain for which they were tested (Bossel 1991; King et al. 1990). Entire stands may also be destroyed at suitably randomized intervals through disturbance, so that the entire successional development can be reinitialized. In spite of the assumptions of spatial homogeneity, and simplistic growth representations, gap models are often able to simulate successfully the observed spatial distribution of forest structure (age, tree size and species composition). Part of the reason for this success must be that the randomized variability in growth and regeneration processes applied to individual trees and plots compensates for the lack of simulated variability in sites and climate. An obvious further explanation is that many gap model simulations have been calibrated in the area from which field data were obtained (i.e. they have a strong empirical basis).

In the present work, a novel enhancement is being investigated to overcome some of these apparent limitations. It is proposed that the variation among site types observed in reality can be represented as a distribution of distinct site types. In the model, this distribution would be represented as an "ensemble" of 10 to 20 or more patches, with differing site characteristics (soils and topography) stochastically distributed in proportion to those observed in reality (Figure 2). Further, the patches within each ensemble are considered to be in intimate spatial contact - hence resembling a sample of the heterogeneous forest mosaic. Forest growth on each patch is still simulated separately, but stand development is no longer considered completely independent of other patches, because some factors are allowed to affect the entire ensemble. These factors include climate, disturbance events and seed dispersal. In particular, a disturbance event occurring in any one of the patches within the ensemble has the possibility of spreading to all the others, through some form of contagion

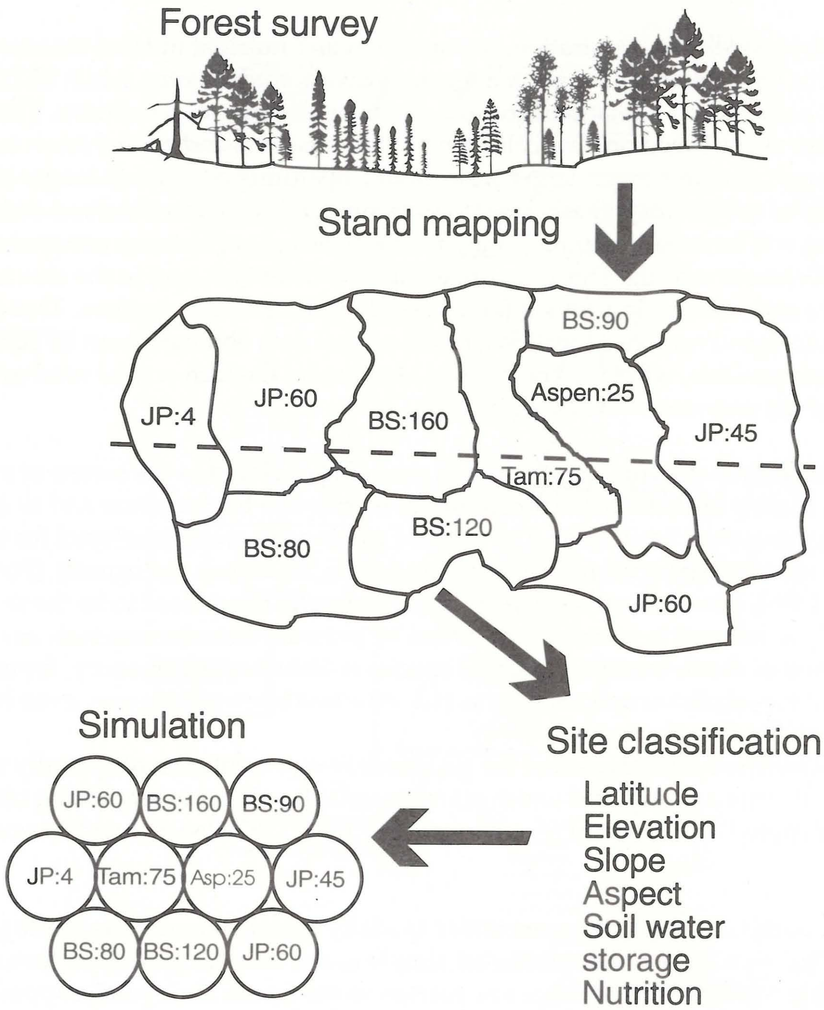

Figure 2. Diagram showing proposed representation of forest heterogeneity by a plot ensemble. Given a surveyed and mapped area of a typical piece of boreal forest mosaic, the range of structures illustrated in the section at top, is attributable to the effects of growth, competition and disturbances, and to the site characteristics of each patch (soil type and topography). In the model, the 10 patches are simulated as spatially connected sample plots (of equal area), with each plot awarded site attributes derived from the observed distribution of site variables.

(such as wildfire, or insect flight). This contagion process must be considered separately from the disturbance hazard (stand susceptibility to disturbance effects) which must be assessed on the basis of successional age, species composition, litter accumulation and environmental factors.

Each ensemble can be considered as a sample of a much larger area, which will be referred to as "a landscape" to signify that it may contain a considerable amount of visible variation (hills, lowlands, wetlands, lakes etc.). Somewhat arbitrarily, each landscape will represented by a 10 km square, which can be located on a map, and hence subjected to topographic and climatic conditions typical of that area. Initially, it will be assumed that all the topographic and soil variation contributing to the range of site types found within each square can be adequately represented by a single patch ensemble.

The forest ecosystem model is required to simulate biomass over age relationships for different site types, generating data in a manner analogous to a real forest biomass inventory. In the same way that real forest inventories are carried out at discrete intervals in time, the model is used to generate a "snap-shot" of the structural composition of the simulated forest stands, for example at 10-year intervals. These simulated stand data can be used to derive the growth functions used by the CBM-CFS (i.e. Metamodel II), in exact analogy to the use of the Canadian forest biomass inventory data base (Bonnor 1985), as reported in Kurz et al. (1992).

Under past climate conditions, the output from the model can be compared to records of forest inventory (where these are available), to provide validation of the approach, with the proviso that human influences may need to be considered. Once it has been established that the model does work satisfactorily for the observational record, it will be used to explore future responses, probably using climatic projections derived from GCM predictions of future climate. Hence, it should be possible to estimate future carbon budgets for the region of the BFTCS, and by extending this work, to the boreal forest as a whole, and eventually to other Canadian forest biomes. If the model can successfully simulate the currently observed forest structure on the one hand, while producing credible estimates of stand-level processes (such as spatially-averaged evapotranspiration and net CO_2 flux) on the other, then there is increased confidence that it is working correctly.

CONCLUSIONS

The total C budget of the Canadian forest sector is believed to be very sensitive toecological processes operating at the scale of individual forest stands. In order to reliably predict the effects of possible future changes in climate and management on the national C budget over the next 50-100 years, a mechanistic simulation of ecosystem responses will be essential, though successful development of such a model is a challenging task.

A likely approach to achieving this objective is to use a nested hierarchy of three levels of simulation, linked by two metamodels where output data from one level are used to generate response functions as drivers for the next level up. The three levels of simulation are (1) stand-level ecophysiology; (2) forest ecosystem dynamics, including the effects of spatial heterogeneity and disturbance contagion and (3)regional- or national-scale C budget assessments, ultimately linked to large scale climate models. If anticipated changes in climate do occur during the next 50-100 years, then the consequences for the Canadian forest industry could be of great socio-economic significance. Advance warning of the effects of these changes, as provided by the integrated large-scale carbon budget model described here, will give policy makers more opportunity to explore management options to prepare for and mitigate the possible adverse consequences.

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DYNAMIC TAPER MODELS: MODELLING TREE SHAPE OVER TIME

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ABSTRACT

Forest management is increasingly becoming more intensive. Therefore, the need for relevant, accurate, timely, and cost-effective forest resource information on the current and future inventory is becoming very important. Understanding and modelling taper changes over time will provide some of the information on both current and future inventory.

The objectives of this study were to investigate the changes in tree form and taper over time as affected by changes in tree, stand and site factors, and to develop a dynamic taper function for dominant and codominant trees of interior lodgepole pine (*Pinus contorta* Dougl.). To meet these objectives, permanent sample plot data from Alberta and detailed stem analysis data, including radial increments over the stem, from the Interior of British Columbia were used. Existing taper equations were considered as possible candidates for both examining taper over time and modelling the taper. A simple geometric equation that describes the radius at different heights for known shapes (e.g., cylinder, cone, and parabola) was selected for examining taper changes. The Kozak (1988) taper function was modified to model these shape changes.

The results of the examination of stem taper over time indicate that the ratio of diameter outside bark at breast height (dbhob) to tree height, ratio of crown length to height (crown ratio), and stand density contribute greatly to stem taper changes with time. Young trees have a fairly constant parabolic shape, regardless of stand density. However, as trees age, variations in stem shape appear for different stand densities, as reflected by the ratio of dbhob to height, and the crown ratio.

This initial examination was used to model tree taper over time. The developed function was compared to the Kozak (1988) static model using a reserved set of stem analysis data. The dynamic taper function provided estimates that were reasonably close to those given by the static taper model. Dynamic taper modelling was, therefore, considered to be a feasible and practical idea.

Model Demonstrations and Poster Presentations

THE STIM GROWTH MODEL

by G.M. Bonnor[1], R.J. De Jong[1], P. Boudewyn[1] and J.W. Flewelling[2]

INTRODUCTION - by G.M. Bonnor

Development of the STIM growth model started in September 1990, when a presentation was made to the B.C. Forest Productivity Councils to solicit their support and cooperation.

STIM is designed for inventory updating, allowable annual cut calculations, and management planning. It is not designed to be a silvicultural decision support system or learning tool like the TASS model.

STIM has been implemented for Western Hemlock not because we need another hemlock model but because we have good data for that species. Having developed a good model using a superior data set, we will next use the results to implement the model for other species, including mixed species.

DEMONSTRATION - by R.J. De Jong and P. Boudewyn

1. Scenario 1 - Introduction to WINSTIM. A simple and easy-to-follow introduction to STIM would be accom plished by generating a stand and growing it x number of years, and by viewing the results with various options. The mouse would be used at every step. The course of action is explained below. Also, refer to Fig. 1.

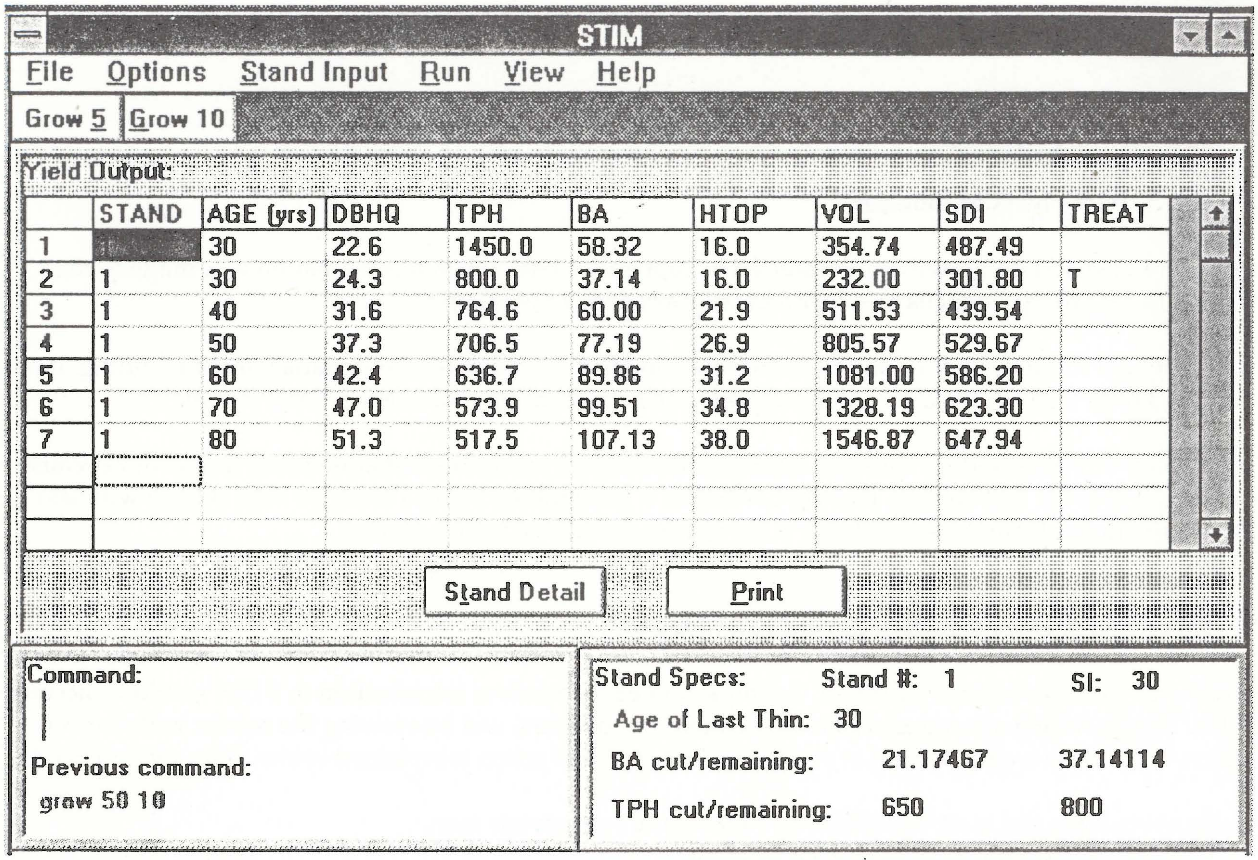
   a. Run windows and start WINSTIM by clicking the appropriate icon.
   b. Use default parameters in the OPTION menu.
   c. Generate a stand in the STAND INPUT menu (use SI=35, Topht=20).
   d. Grow the stand 80 years using the GROW hot keys. Change the reporting period to 10 years after the first growing sequence.
   e. View the results output to the screen, and graphically by using the VIEW menu.

2. Scenario 2 - Management and graphical abilities of WINSTIM. This would follow scenario 1 by inputting a simple tree list, and demonstrating how to thin and grow the stand, and how to graphically overlay different growth projections.

   a. Input a simple tree list (dbh1-dbh4=15, 20, 25, 30; ht1-ht4=11, 13, 14, 16; tph1-tph4=300, 500, 400, 250); view the tree list; grow it for 10 years with the hot keys; and thin it using the RUN menu (leave 800 tph with a d/D=0.9).
   b. Explain the output.
   c. Grow the stand to age 80 using the command line.
   d. View the results using the VIEW menu. Graph previous runs to show STIM's flexibility. Overlay the yield output of this scenario (thinned) with that of scenario 1, to compare the outputs (we can't over lay as of this date).

These scenarios should demonstrate most of STIM's capabilities. The key is to keep it simple and straight-forward, so that the audience can follow everything that is shown. If the audience requests us to show more of the model, or some advanced feature like batch processing, then we should be prepared to do so.

The demonstration is performed using one of our computers and the LCD projection panel, which allows computer screens to be projected through an overhead projector. One person is at the computer to input the data and run all of the scenarios. A second person is at the overhead projector to explain the various features of STIM.



	STAND	AGE (yrs)	DBHQ	TPH	BA	HTOP	VOL	SDI	TREAT
1		30	22.6	1450.0	58.32	16.0	354.74	487.49	
2	1	30	24.3	800.0	37.14	16.0	232.00	301.80	T
3	1	40	31.6	764.6	60.00	21.9	511.53	439.54	
4	1	50	37.3	706.5	77.19	26.9	805.57	529.67	
5	1	60	42.4	636.7	89.86	31.2	1081.00	586.20	
6	1	70	47.0	573.9	99.51	34.8	1328.19	623.30	
7	1	80	51.3	517.5	107.13	38.0	1546.87	647.94	

Fig. 1. Main screen for STIM

Validation - by J.W. Flewelling

The STIM model for western hemlock growth is at a partially completed stage. All empirical submodels have been developed, though many of the submodels are not in final form. The primary purpose of this validation is to learn if the model components interact in ways which introduce ne unexpected errors. A secondary purpose is to identify any mathematical or programming errors that cause the growth program to blow up or act in other unexpected ways.

The validation program uses input/output code custom written for the validation. The growth routines are same as in STIM and WINSTIM - thereby assuring that the routines being validated are the same as will eventually go to the user.

The growth data used for the validation are the individual growth periods on all of the plots used in developing STIM.

The validation worked in that mechanically we were able to project every plot that we sought to project. Furthermore, most of the significant mean errors were all known to us in advance from the residual analyses on the fitting equations. The most noteworthy results are the mean errors in survivor basal area increment - contrasted between thinned and unthinned. The stand model has an explicit 'thinning effect'; the tree model does not. The fact that the thinning bias for the tree model is not much larger than for the stand model suggests that much - but not all - of the thinning effect is explainable in terms of the stand structure variables used in the tree model. Overall, the variance of projections using the stand model were considerably less than those from the tree model (run by itself). This tends to confirm the usefulness of the integrated approach, while the thinning results show that stand averages may not be suffient for all growth prediction purposes.

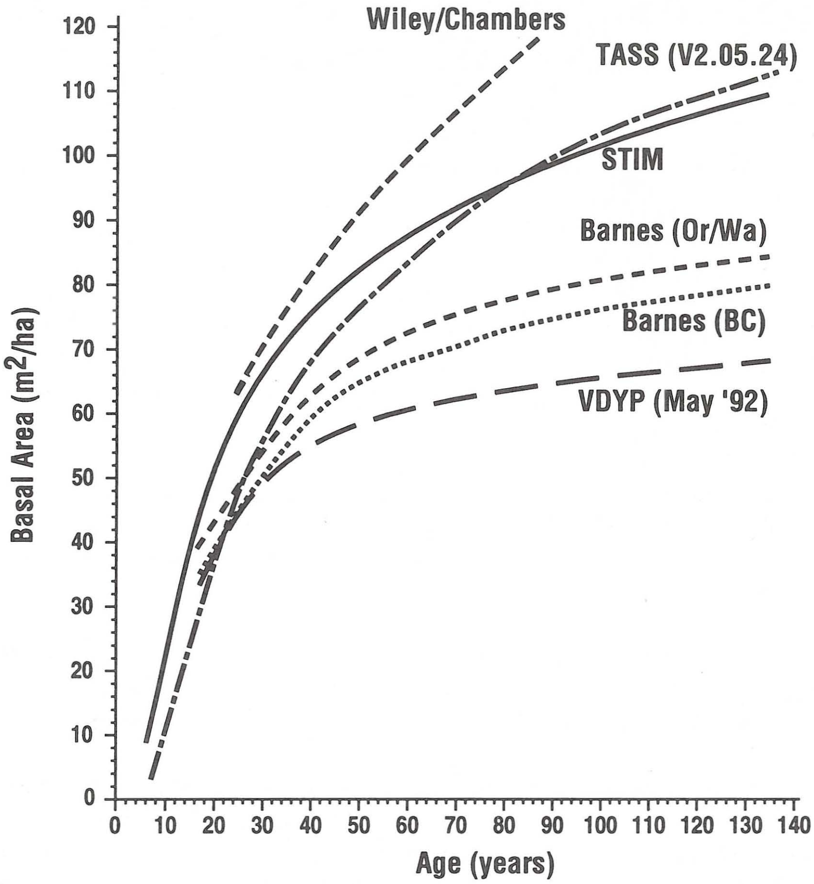


Fig. 2. Comparison of growth models

Sensitivity runs were made to ages beyond that in our data base. There was very little separation in predicted yields at older ages between high sites and low sites. Other regional models show a large separation. Though this problem could be addressed with a reformulation of empirical growth equations, we have made the decision to obtain and use more older-age data.

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LPMPB: A VARIABLE DENSITY LODGEPOLE PINE GROWTH AND YIELD MODEL FOR MOUNTAIN PINE BEETLE IMPACT EVALUATION

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Victoria, B.C. V8Z 1M5

Smithers (1961) published yield tables for lodgepole pine in Alberta and B.C. While these tables permitted estimation of growth and yield up to age 160, they did not include variable density effects. Johnstone (1976), on the other hand, produced variable density yield tables for lodgepole pine in Alberta, but the equations on which these equations were based only permit prediction up to age 100. Thomson (1987) showed how these yield tables were comparable to a large extent.

Based on the results of the analyses leading to the 1987 paper, I developed a variable density lodgepole pine growth and yield model that covered ages 20-200 in unmanaged stands. The model is table-driven, based on Smithers' (1961) tables extrapolated to age 200. The table values are modified for density effects by correction factors calculated from Johnstone's (1976) tables.

The model generates diameter distributions which can be affected by mountain pine beetle (MPB) effects. The manner in which this modification works has not yet been documented, but is based on probability of mortality being a function of a trees position in the diameter distribution, and on the severity of the MPB.

There are only a few inputs required to run the model (Fig. 1), and these reflect the kind of information that might be available from normal sampling. Stand age and density (stems per hectare) must be defined, and a reference age provided for site index output. If a zero-valued Beetle Pressure Index is entered, the system functions purely as a lodgepole growth and yield model. The output file name has a default value of "OUT", which is used in conjunction with different type extensions for the various yield tables produced. Up to four different yield tables are produced (Fig. 2); only the first two of these tables occur when a zero-valued Beetle Bressure Index is used.

If a non-zero value for Beetle Pressure Index is entered, an additional entry field for the starting year of the outbreak is included. This permits a stand to be defined at one point in time and the impact of an outbreak at a different time evaluated. Note that the impact is only in terms of mortality at the time of the outbreak. There is no projection of stand growth beyond 10 years after the outbreak starts.

On pressing <RETURN> to continue, a second data entry screen is presented.Having specified the age and density, a third parameter is required to fully specify the stand growth. This third parameter can be either dbh, height, basal area, volume or site index. When the appropriate selection is made, an entry field is presented, with guidance on the upper and lower limits to the values appropriate for the age and density specified. By specifying age, density and a third parameter, the stand trajectory from age 20 to age 200 is defined.

The stand table generated for the values in Fig. 1 is illustrated in Fig. 2. The diameter distribution in 5-cm classes is given at 10 year intervals (Fig. 3), with a line in the table, flagged by an asterisk, showing the conditions entered. A graph of the distribution at up to three ages can be produced (Fig. 4). The yield table (not illustrated) shows dbh, height, basal area and volume changes with age. These can also be graphed.

When a non-zero Beetle Pressure Index is used, the model projects changing index values over a ten year period and applies them to the diameter distribution (Fig. 5). A graph of three of these years shows the larger trees rapidly succumbing to beetle attack (Fig. 6).

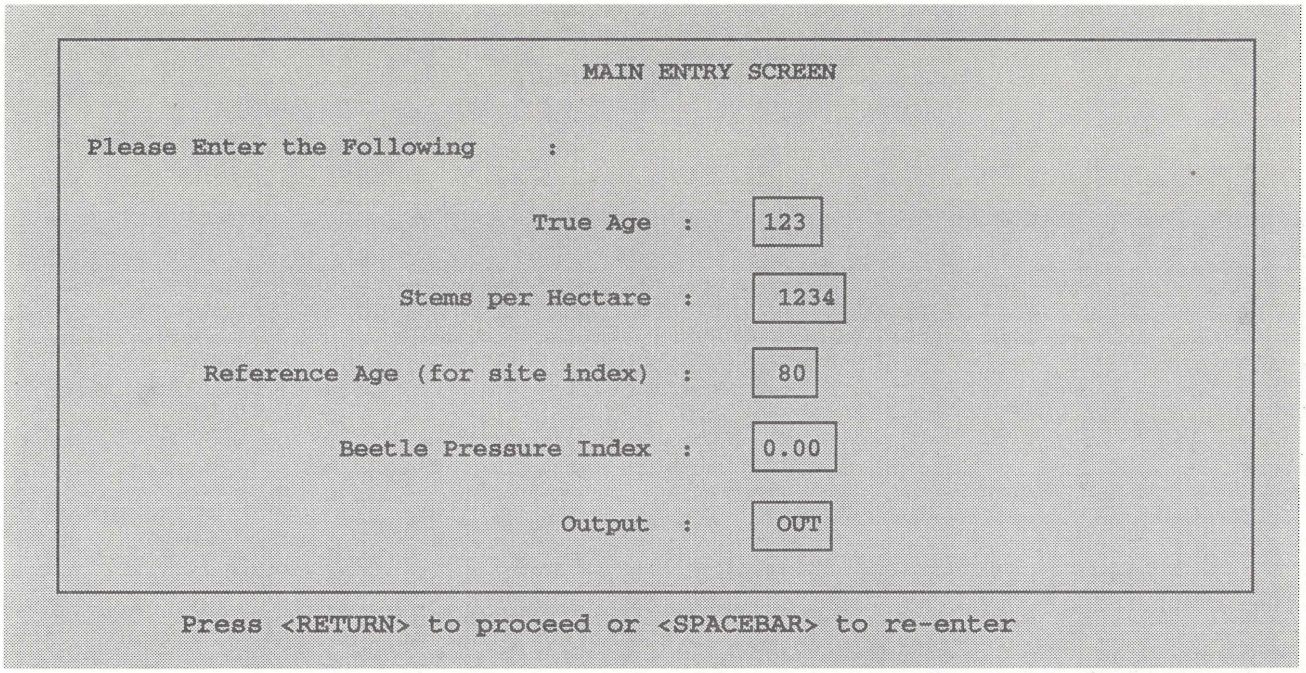

Figure 1. The main data entry screen.

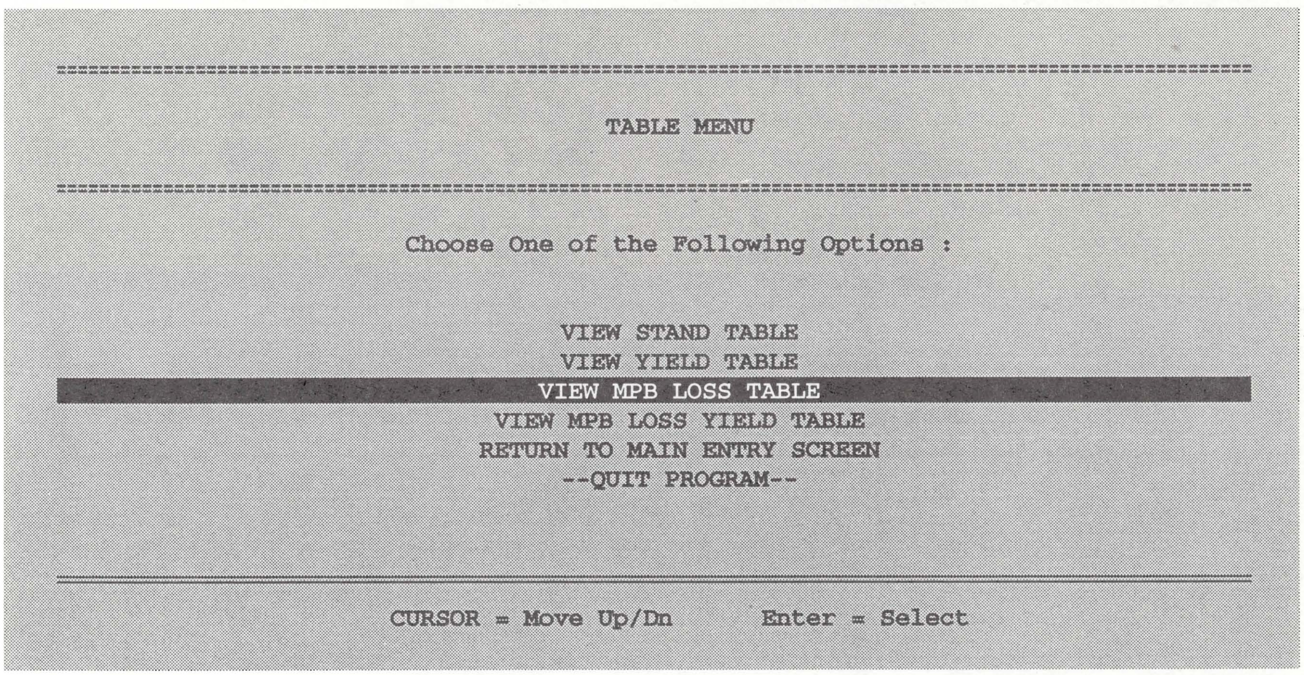

Figure 2. The output table selection screen.

Summary

LPMPB is an easy-to-use variable density lodgepole pine growth and yield model for unmanaged stands. By specifying conditions at one point in time, the model can project back to age 20 and forward to age 200 to provide a complete stand trajectory through that point. Mountain pine beetle effects can be simulated to generate impacts in the ten years following the initial attack.

Diameter Classes SI (Ref. Age 80) = 18.9

DBH	AGE	SPH	5	10	15	20	25	30	35	40	45	50	55	60
4.7	20	6939	5955	984	0	0	0	0	0	0	0	0	0	0
8.3	30	3883	1651	1873	359	0	0	0	0	0	0	0	0	0
10.7	40	2869	602	1505	717	45	0	0	0	0	0	0	0	0
12.7	50	2345	237	981	923	204	0	0	0	0	0	0	0	0
14.6	60	2006	93	575	899	397	42	0	0	0	0	0	0	0
15.9	70	1791	50	368	769	496	108	0	0	0	0	0	0	0
17.3	80	1611	26	236	604	542	191	12	0	0	0	0	0	0
18.3	90	1489	16	158	487	548	241	39	0	0	0	0	0	0
19.3	100	1384	0	118	380	519	292	75	0	0	0	0	0	0
20.1	110	1311	0	90	309	484	320	102	6	0	0	0	0	0
20.8	120	1252	0	68	263	444	332	129	16	0	0	0	0	0
*21.0	123	1234	0	64	253	433	332	133	19	0	0	0	0	0
21.3	130	1192	0	57	228	406	332	143	26	0	0	0	0	0
21.8	140	1145	0	49	196	375	334	155	36	0	0	0	0	0
22.4	150	1098	0	42	168	340	334	168	46	0	0	0	0	0
22.9	160	1058	0	37	147	307	326	181	58	2	0	0	0	0
23.3	170	1023	0	33	133	283	317	187	65	5	0	0	0	0
23.6	180	992	0	30	122	264	309	190	69	8	0	0	0	0
23.8	190	965	0	27	113	248	301	193	73	10	0	0	0	0
24.1	200	942	0	25	106	236	294	194	74	13	0	0	0	0

Produce Graph Return to Table Menu

Figure 3. The stand table for the inputs in Figure 1.

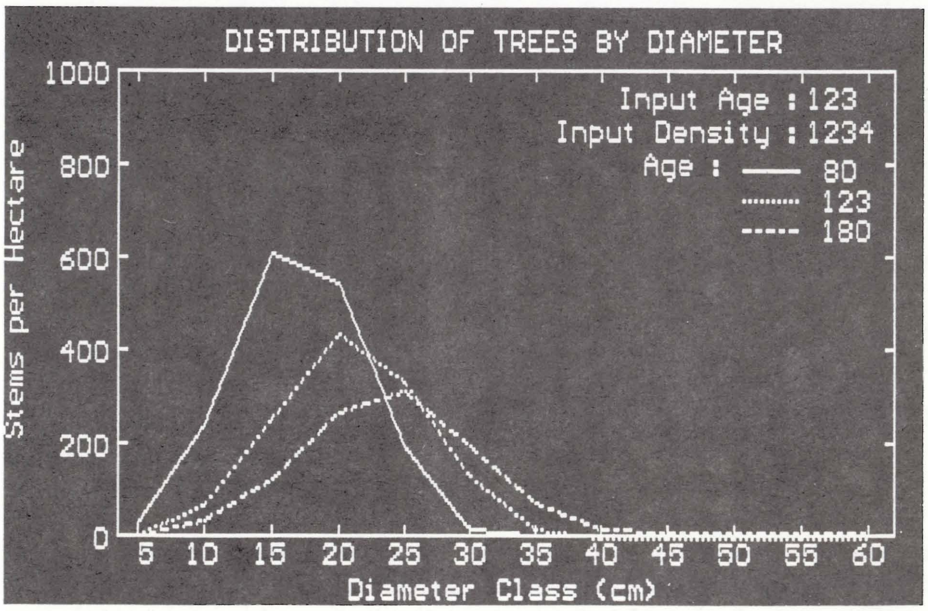

Figure 4. The diameter distributions from three ages in Figure 3.

10 YEAR MPB LOSS TABLE

AGE = 120 BPI = 0.60 SI = 18.9 (Ref. Age 80)

			Diameter Classes											
YEAR	SPH	DBH	5	10	15	20	25	30	35	40	45	50	55	60
0	1252	21.0	0	68	263	444	332	129	16	0	0	0	0	0
1	1112	19.9	0	68	263	444	290	46	1	0	0	0	0	0
2	988	19.1	0	68	263	444	205	8	0	0	0	0	0	0
3	898	18.5	0	68	263	444	122	1	0	0	0	0	0	0
4	838	18.0	0	68	263	444	63	0	0	0	0	0	0	0
5	804	17.7	0	68	263	444	29	0	0	0	0	0	0	0
6	787	17.5	0	68	263	444	12	0	0	0	0	0	0	0
7	780	17.5	0	68	263	444	5	0	0	0	0	0	0	0
8	777	17.4	0	68	263	444	2	0	0	0	0	0	0	0
9	733	17.3	0	68	263	402	0	0	0	0	0	0	0	0
10	687	17.1	0	68	263	356	0	0	0	0	0	0	0	0

Produce Graph Return to Table Menu

Figure 5. The mountain pine beetle loss table from an outbreak starting at age 120.

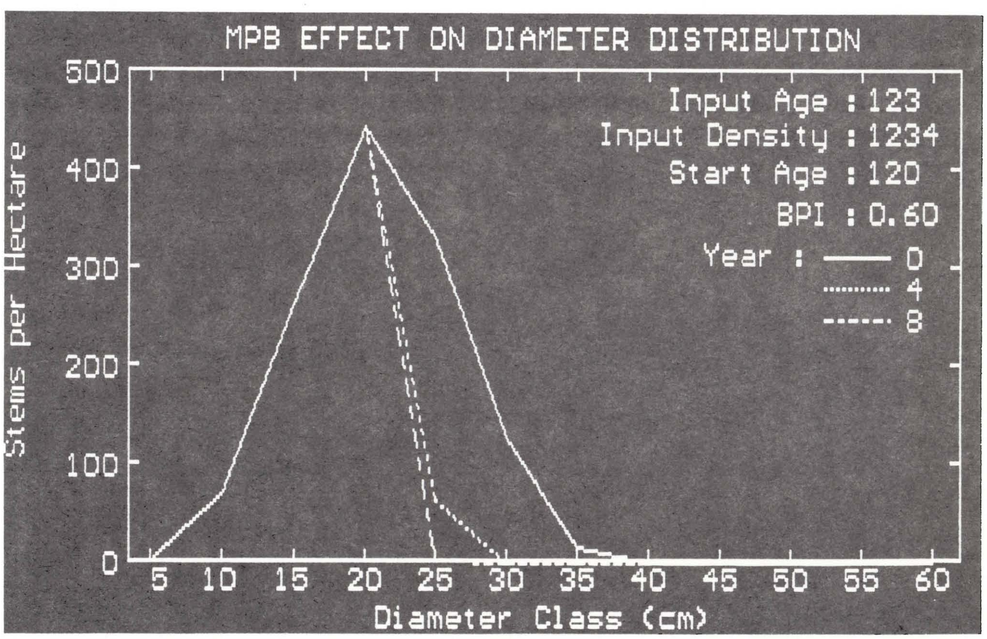

Figure 6. The changing diameter distribution during the outbreak represented in Figure 5.

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Thomson, A.J. 11987. Comparison of lodgepole pine yield tables. Can. J. For. Res. 17: 1110-1114.

Figure 5. The mountain pine beetle loss table from an outbreak starting at age 120.

Figure 6. The changing diameter distribution during the outbreak represented in Figure 5.

A PC-BASED INTERACTIVE STAND DENSITY MANAGEMENT MODEL FOR MANAGED BLACK SPRUCE STANDS[1]

by P.F. Newton[2]

The model illustrates expected stand development trajectories (n=8) from 5 to 60 years (breast-height age) for various initial spacing regimes employing a stand density management model (Newton, P.F. and Weetman, G.F. 1993. Stand density management diagram for managed black spruce stands. For. Chron.). Resultant yield estimates are tabulated by 5 year intervals within an output data file. Yield production functions with operability criteria superimposed are also illustrated. The model is currently configured for insular Newfoundland but can be readily re-calibrated for other regions by changing the site index function. The model output devices are configured as a VGA supported screen and either a HP LaserJet or a HP DeskJet 500 printer. The user must specify through the interactive screen prompts: (1) site index (i.e., dominant height at 50 years (breast-height age (Newton, P.F. 1992. Base-age invariant polymorphic site index curves for black spruce and balsam fir within central Newfoundland. North. J. Appl. For. 9:18-22)); (2) minimum initial spacing regime; (3) density interval between the eight possible spacing regimes; (4) operability criteria consisting of minimum merchantable volume per hectare and maximum number of stems per cubic metre; and (5) output device for the diagrams. Further model development will include incorporating pre-commercial thinning treatments as data bases become available.

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1 Presented at Forestry Canada's Annual Modelling Working Group Meeting, Pacific Forestry Centre, Victoria, B.C. February 8, 1993.

2 Forestry Canada, Newfoundland and Labrador Region, P.O. Box 6028, St. John's, Newfoundland, Canada A1C 5X8.

Establishment Reports

NEWFOUNDLAND AND LABRADOR REGION

Stand density management models for natural and managed black spruce stands have been developed (Newton and Weetman 1993). A Growth and Yield Workshop was held in October 1992 in CornerBrook, Newfoundland. Approximately 40 people attended, representing the federal and provincial governments, forest industry and local educational institutions. Current modelling activities were reviewed with presentations from all major players within the region. The primary focus of the Workshop was to demonstrate the practical utility of stand density management models in black spruce management to silvicultural planners, unit foresters and forest managers. NLR continues to provide follow up support for the implementation and usage of the models to end users. Other work was carried out involving the assessment of the precision of remeasurement procedures of PSP's, under the auspices of a contracture agreement. Further evaluation of balsam fir thinning responses was also completed. Provincial and industrial agencies have shown an increased interest in Growth and Yield research and have become active participants in various areas.

Peter Newton

QUEBEC REGION

Dynamic of spruce budworm population - Jacques Régnière

- To construct survival tables for spruce budworm under a variety of ecological conditions
- To develop simulation models of spruce budworm population dynamics
- To use the information obtained and the models developed to create decision-making tools for spruce budworm control.

Growth and yield - C.-H. Ung, Denis Ouellet, Richard Zarnovican

- To develop techniques of forest inventory
- To validate hypotheses governing production models
- To relate stand and tree characteristics to productivity and wood quality
- To examine the role of growth processes on the development of trees and stands
- To develop the appropriate silvicultural strategies for management series.

C.-H. Ung

MARITIME REGION

The general areas of activity include:

Dave MacLean: budworm impact modelling;
decision support systems for pest management.

Merve Morgan: hardwood thinning and fertilization studies.

Tom Royama: budworm ecology and population dynamics;

Mike Lavigne: tree physiology;
- process modelling;
- potential applications of radar imaging to forest inventory.

Mike Ker: development of biomass yield models;
- pre-commercial thinning studies in balsam fir;
- site index equation development.

M. Ker

PETAWAWA NATIONAL FORESTRY INSTITUTE

R.M.N. Newnham

In October, the forestry management modeling project (PI-19) hired a recent graduate, Peter Hvezda, from the School of Computer Science at Carleton University to build a graphical user interface (GUI) for inputting data for the LOGPLAN model along the lines described at the Kananaskis meeting of the group. The GUI is being developed using Smalltalk, probably the most widely used object oriented programming system (OOPS). Progress has been remarkably rapid. It is now possible to rapidly construct flowcharts on the screen and to input data using windows obtained by clicking on the stores and activities. One or two minor (hopefully!) bugs remain to be sorted out but the GUI should be ready for operational testing soon. The Smalltalk system appears to be ideal for developing GUIs and will undoubtedly be used to develop interfaces for some of the project's other planning models.

M. Penner

Fieldwork for BOREAS and the Forestry Canada Boreal Forest Transect Case Study (BFTCS) commenced last summer at PNFI. This was a dry run of field sampling procedures in conjunction with Godelieve Deblonde from CCRS and concentrated on obtaining leaf area index estimates (LAI = area of foliage per unit of ground area) both directly (destructive sampling) and indirectly (LiCor lai-2000). Results were good for red pine but not as good for jack pine. LAI appears to be highly correlated with basal area growth and may have implications for remote sensing of growth.

The black spruce density management diagram for black spruce is pretty well wrapped up. D. Smith, under contract with OMNR, continues working with the SFPP (Spruce Falls Power and Paper, Co.) database. A preliminary simulation system of forest growth for black spruce of the Clay belt has been completed. Different growth curves for height, basal area, volume and species composition were derived.

Current studies involve looking at linking the 1984 biomass inventory with the 1986 national volume inventory. The objective is to use the resulting relationships to predict national biomass estimates using the current inventory. Preliminary work involves using neural nets where data are good. The eventual product will probably be a combination of the derived relationships and a series of rules for assigning values where information may be weak or nonexistent.

The E-mail bulletin for the working group has been set up by defining a distribution list containing at least one representative from each establishment. Communications can be made through the Vax systems located in each establishment.

D. Burgess

The main activity has consisted of collecting growth information on white pine at the Cartier Lake Silvicultural area. This experimental site was originally laid out in 1971 in a mixedwood stand consisting of intolerant hardwoods in the overstorey (aspen and white birch), and of white pine in the understorey (with some red pine, white spruce, jack pine, balsam fir, white cedar, tamarack, and tolerant hardwoods). Control plots were established, and treatments consisted of removing the intolerant hardwoods in the overstory, which resulted in three basal area classes based on residual white pine, red pine, and white spruce. The effects of these silvicultural treatments on stand structure and seedling performance has been monitored for the last two growing seasons. Models will be eventually derived from these results.

G. Larocque
The development of polymorphic site index curves for black spruce in the Clay belt from the SFPP data set went through a second phase last fall. This is an on-going project with M. Penner and D. Smith from PNFI, and D. Archibald and John Parton from the Ministry on Natural Resources in Timmins. These curves will be used in conjunction with stand density management diagrams developed for black spruce. As the data set was greatly modified (corrections and addition of new plots), all the work undertaken in 1991 was repeated. Some operational groups were merged to provide curves that would be more practically applicable by the field forester. They will appear in the local newsletter of the OMNR in the Northeast.

The development of a process-oriented growth model for red pine has been an on-going project for some time. It is expected that much progress will be made this year. The remeasurement of permanent sample plots at PNFI will provide complementary information. Inquiries have been made with Jeff Baldock, soil scientist at PNFI, to develop a process-oriented model for carbon partitioning. Importance will be given to the interface between below- and above-ground processes.

G. Larocque

FOREST PEST MANAGEMENT INSTITUTE

Richard A. Fleming
The Forest Pest Management Institute (FPMI) is one of Forestry Canada's two national research institutes. FPMI provides national leadership and capability in the development of new or improved pest management products and strategies for their use. Environmental quality and public health and safety are major considerations in this endeavor.

The Institute's program is broad and complex and involves an extensive variety of discipline specialists. The Biological Systems Analysis Project (FP-23) conducts most of the modelling work at FPMI. The project also cooperates with scientists from other Forestry Canada establishments and with scientists outside Forestry Canada on a national and international basis. Systems analysis techniques are developed and applied to the design, conduct, interpretation, and synthesis of a broad spectrum of experiments that cut broadly across FPMI's research program. In particular, expertise in experimental design, statistics, and modeling is provided in many studies related to the effectiveness and environmental impact of pest control materials and methods. In this way the project tries to develop important information and interpret results in a form promoting eventual field application. Through modeling, project FP-23 also promotes an integrated approach to pest management by helping to develop ecologically sound and cost-effective strategies for combining the use of new pest control products with those currently in use. Thus FP-23 has a major role to play in bringing potentially new options for forest pest management into operational use.

The thrusts in modeling at FPMI in 1991-92 fell in four main areas:

i) **Environmental Impact**
The Fleming, Holmes and Busby (1992) paper wrapped up the *interlaboratory comparison* in measuring the association of aerial applications of Zectran with cholinesterase levels in songbird brains. Multiple linear regression methods showed that the ChE estimates of the two labs on the same group of birds were poorly correlated and differed significantly. In contrast, separate statistical analyses produced the same general trends in each data set. These results suggested that either (a) the differences between labs were not important and the similarity of conclusions resulted from consistency in the internal structure of the data sets produced by each lab, or (b) that the differences point to fundamental flaws in procedure in at least one of the labs, and that only luck produced similar conclusions. Because of the consistency in results for the two labs in testing additional, unrelated hypotheses, we consider the first possible inter pretation more likely.

Climate change. To date this work has revolved around statistical analyses of long term climate-pest phenology interactions.

ii) **IPM/Decision Support**

FIDS-type survey data were used in *testing large scale spruce budworm-forest simulation models* which were developed as decision support tools for forest management (Fleming and Shoemaker 1992). Among other things, this analysis illustrated some of the problems involved in modeling processes which operate at fundamentally different time and space scales (Fleming 1991).

B.t. respray decisions. Recently some operational sprays of B.t. have had inconsistent effects. Fleming and van Frankenhuyzen (1992) showed that under current field protocol, appropriate decisions about applying a second B.t. application (for greater consistency) could not be based on field measurements of the B.t. dose ingested by spruce budworm larval populations shortly after the initial spray. Changes in field protocol that might facilitate such predictions were suggested. Study completed.

iii) **Pest Damage Thresholds and Assessment**

Seed and cone crops. Development of sampling plans and life tables for monitoring damage and esti mating crop size for jack pine and black spruce seed orchards.

Long-term study to determine the *impact of spruce budworm defoliation* on subsequent balsam fir foliage and wood production. One objective of this work is to develop damage thresholds for budworm defoliation of balsam fir. Fleming and Piene completed period (1992b) and cohort (1992a) models of needle fall in spaced, protected stands. Models of needlefall in unspaced, but protected, stands are under development.

iv) **Pest Control**

Vegetation management. Development of *improved-use strategies for glyphosate.* Pitt et al. (1992) and Thompson et al. (1992) showed that reducing glyphosate application rates to half that of the normal operational rate used in New Brunswick resulted in negligible declines in efficacy.

A study centered on attempts to reduce the dosage and emitted volumes of *nuclear polyhedrosis virus* for gypsy moth control was initiated.

PUBLICATIONS:

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Fleming, R.A., and van Frankenhuyzen, K. 1992. Forecasting the efficacy of operational Bacillus thuringiensis Berliner applications against spruce budworm, Choristoneura fumiferana (Lepidoptera: Tortricidae), using dose ingestion data: Initial models. Can. Ent. 124(6):1101-1113.

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Thompson, D.G., Pitt, D.G., Fleming, R.A., and Kettela, E.G. 1991. Glyphosate efficacy on eastern Canadian forest weeds - Part I: Experimental design and on-target deposit. Can. J. For. Res. 22:1151-1159.

R.G. Fleming

ONTARIO REGION

A) Entomology: Members of the entomology modeling group consisting of Don Wallace, Vane Nears and Barry Lyons are continuing their work in entomological modeling as reported last year with minor changes. Jens Roland was the successful candidate for the insect population dynamics position vacated by Tim Lysyk about three years ago. Jen joined us recently from the Northern Region, Forestry Canada and is mainly interested in studying population dynamics of saw flies mainly via application of GIS. Much of the work of the group, however, remains pretty much the same as reported in the last meeting.

B) Forest Fire: Tim Lynham has been involved in a joint effort with Dave Martell of University of Toronto regarding a national database of experimental fires and reports that: Canadian forest fire researchers have collected over a million observations on weather, fuel moisture and fire behavior related to a massive test-fire program that was conducted from 1931 to 1961. Approximately 20,000 test fires were conducted at 11 field stations. across Canada. In 1960 a project began to transfer the original field notes to computer files so that the data could be analyzed on mainframe computers. Late in 1989, PNFI provided a tape copy of the above information to Ontario Region and the initial work began in preparing a national database on such information.

C) GIS Related Studies: Richard Sims reports on a new cooperative study " GIS Methodologies to Develop Spatially-Based Boreal Ecosystem Models in the Rinker Lake Research Area, NW Ontario". The objective of this study at FCOR is to develop prototype, spatially-based and GIS- assisted integrated ecosystem models for a representative boreal forest area in NW Ontario. Using an analytical GIS approach, the study will integrate a variety of parameters including forest stand, vegetation, soil, site, surface elevation, climate, etc. to construct and test "ecosystem models". The results will provide a methodology and a case study application which will be of direct interest to forest and resource managers. Those involved in this study include R. Sims, K. Baldwin, K. Lawrence, D. Mckenney, and B. Mackey of FCOR, D. Welsh of Canadian Wildlife, and P. Howarth of the Earth Observations Lab, University of Waterloo. This study is funded through NODA. In addition to the above Richard and his colleagues are involved in:

1) Climate change modelling of major boreal tree species in NW Ontario. He is working with B. Mackey on the analysis of a digital elevation model NW Ontario. They have overlain the Canada climate Centre's gridded scenario for CO2 doubling, and are showing the potential climatic ranges for several major boreal tree species in NW Ontario. The have prepared a paper for a major Chicago conference on climate change for beginning of April, 1993, on this work.

2) GIS modelling of FEC Type maps in the Roslyn Lake area, NE of Nipigon, Ontario. This work with K. Lawrence, our new GIS Tech. is looking at some field survey work that was done in 1987-88 to field map FEC types for a 100 sq. km area. They have constructed soils maps and vegetation maps for the area, and are using the GIS to blend these layers and conventional FRI polygons to provide better insight to distribution of tree species, and the development of derived/interpreted ecosystem maps.

3) Under a NODA contract to Geomatics, Burlington, they are examining the use of SPOT imagery overlain on an area near Ignace, Ontario, and it's role in improving forest planning operations (harvesting/silvi culture) as an add on to conventional FRI and surficial deposit information (as provided by Ontario Land Inventory and the Northern Ontario Engineering, Geology and Terrain Survey (NOEGTS). This work is ongoing, in cooperation with CP Forest Products in Thunder Bay, Ont.

D) Plant Physiology: Gary Hogan, Fred Beall and their three PDFs are involved in:

1) As part of an ENFORfunded project examining physiological and biochemical indicators of superior growth and environmental fitness of hybrid poplar, they have been employing a process model of poplar growth called ECOPHYS. ECHOPHYS was developed by a group from the USDA Forest Service

Labs in Grand Rapids, MN. and Rhinelander WS. They are using the model to identify and quantify important clonal differences in physiological parameters such as photosynthetic light response, respira tion, and phenology. This has involved collecting the data necessary for calibrating the model for the clones they are using and validating the model results against field data. The results to date indicate that they cannot completely predict growth from the photosynthetic and morphological data they have collected. It appears that they will have to collect clonal specific data on carbon partitioning before the can improve the predictive ability of the model for the clones they are using.

2) Our physiologists are also assisting the ECOPHYS group in the future development of the model. Current priorities for model development include: modelling below ground biomass accumulation and distribution, improving the modelling of growth and maintenance respiration, extending the model past the establishment year, modelling stomatal behavior in order to include pollution and light effects and developing an expert system to simulate the tree's development regulatory system. They are directly involved in the respiration, stomatal behavior and development regulation aspects and are providing data for the other aspects.

E) Growth and Yield and Regeneration: Validation and calibration of the "ONTWIGS" model continued on several data sets from northern Ontario wit very encouraging results. More intensive calibration with larger and more representative data from boreal mixedwood is underway under a NODA funded study with Dr. Y. Wang, a PDF who joined us last June.

"PLANT-PC" was modified and enhanced considerably, its users manual has been completed and should be back from the printers any day now. "FIDMEPC" has been modified somewhat to allow for input file editing appending and other and manipulation. It will be used for the final economic analysis for the growth and yield study wrap. Several new research studies funded by S & T Opportunities, NODA, Model Forest and Boreal Mixedwood project have been undertaken or are in the process of doing so as follows:

1) Dr. Wang and I are also working on an S & T funded project to develop composite site productivity functions for the boreal mixedwood of Ontario. Despite some difficulty in obtaining existing data sets from OMNR, excellent progress has been made on this project resulting in four manuscripts so far.

2) As stated above, Dr. Wang will be fully calibrating the forest growth and yield projection system "ONTWIGS" for the boreal mixedwood in north central Ontario and will demonstrate its application to prospective users over the next three years under a NODA funded project.

3) "MIXPERT" is a project to develop a user friendly knowledge based management supervisory system to evaluate possible silvicultural and management options for the mixedwood portion of the Lake Abitibi Model Forest over the next four years under contract, perhaps with the staff of Algoma University College.

4) Another study to be undertaken shortly involves comparing the relative efficiency of several harvesting methods in boreal mixedwood in Ontario in cooperation with Canadian Pacific Forest Product Ltd. This will be a three year contracted study funded under the boreal mixedwood project.

5) "FEXPERT" is a study proposal to develop a portable interactive and diagnostic aid in forest ecological classification field application. This proposal has received favorable review for submission in the next round of the NODA call for proposals.

F) Silviculture:

1) Art Groot continues on developing a numerical model to investigate aspects of the forest clearcuts envi ronment. The model comprises a solution the one dimensional transfer equations describing the transfer

of heat and water in the air and soil near the surface. The model is applicable to flat, unvegetated, horizontally- homogeneous forest clearcuts. The model has been validated on three forest clearcuts. Bias in predicted soil temperatures was less than 1 degree C on all three sites. Air temperature, water vapor pressure and saturation deficits at 20 cm height were predicted with small bias on two of the validation sites; on the third site bias was larger, possibly because of heterogeneity of the surface. soil water content predictions were sensitive to soil hydraulic conductivity. The model is useful for examining the effects of boundary, surface and soil conditions on the seedling physical environment.

2) Rob Fleming's current modeling initiatives are centred on two areas 1) plant water relations and 2) black spruce seedling establishment following direct seeding. The plant water relation work involves the development of a phenomenological model relating seedling stomatal conductance to environmental variables such as solar irradiance, air and soil temperature, soil moisture and atmospheric humidity. The approach taken is to solve a multiplicative model using nonlinear regression techniques and subse quently employ modeled outputs to estimate daily and seasonal transpiration rates. The work on black spruce seedling establishment is now focused on selecting appropriate probability density functions relating seedling establishment ratios to stocking levels for spot seeding. Further developments will involve using modifying and/or creating appropriate stochastic models to predict stocking and density following aerial seeding as a function of site type, seedbed, seedling rate and climate. These studies are currently being undertaken. No publications relevant to these topics have been produced as yet.

B. Payandeh

PRAIRIE REGION

I.E. Bella

The stand productivity project at Northern, lead by Imre Bella, has three major areas of modelling activities. The first is traditional growth and yield modelling, under Chris Cieszewski, where the main thrust is development of managed stand yield models based on the self thinning rule. A model for lodgepole pine is in the final stages of calibration, but there were several significant achievements along the way. E.g., development of new technology, and using this, the development of a set of new, polymorphic height growth - site index models for all the commercial timber species in Alberta; and the development of density - height growth model for lodgepole pine that describes height growth reduction of trees in relation to stand density.

The second area is the development of decision support systems for forest management, where Richard Yang is leading the charge. The objective is to synthesize all related information in a computerized, user friendly software to facilitate the increasingly complex forest management activities. The system is to include objectives related timber and other uses and benefits as well. Although the prototype is intended for the boreal mixedwood forests in the region, the initial effort is concentrated on essentially pure trembling aspen cover type, for which now a knowledge base system in Hypertext (that includes info on silvics, ecology, stand management, harvesting and utilization), and a prototype DSS with GIS, expert system, data base management and modelling facilities. Map and tending modules are complete, regeneration and harvest modules will be developed next with domain experts' help.

The third area is the modelling of economic and financial analyses under Bill Ondro, with current work on the profitability of white spruce release from trembling aspen competition, profitability of thinning pine, jack and lodgepole, and development of a computer software for financial analyses. Such software will eventually be imbedded in the mixedwood DSS.

D. Price

1. Mike Apps, David Price, Werner Kurz* and Chao Li:

Forest carbon budget and responses to climate change

Primary objectives are to develop better estimates of Canadian forest sector carbon budgets, and to better assess probable future responses of these C budgets to anticipated climate change. Modelling is aimed at integrating better representations of critical forest ecosystem processes, believed sensitive to climate, into a large scale C budget model of the Canadian
Forest Sector (CBM-CFS). It will also integrate other models being developed in the Forestry Canada climate change program (including Hogg and Campbell at NoFC).

Using a three-tier nested metamodel framework, ecophysiological data will be used to develop species level response surfaces ("bottom tier") for use in forest ecosystem models. The latter will be used to develop simulations of forest biomass inventory within a biome ("middle tier"), under various climate scenarios. The output of these simulations will then be used to estimate future carbon budgets using the CBM-CFS ("upper tier"). Biome-level responses will be investigated initially using the ecosystem model validated against data derived from BOREAS (BOReal Ecosystem-Atmosphere Study), and Forestry Canada's boreal forest transect case study (BFTCS). When a satisfactory framework exists (including wetland and soil C dynamics), the approach will be extended to other biomes. Ultimately, it is anticipated that these modelling approaches will be used in NBIOME (Northern Biosphere Observation and Modelling Experiment).

2. Ted Hogg:

Ecosystem processes

The objective is to determine the response of drought-stressed aspen and jack-pine communities (growth, leaf area index and survival) to past, present and future climatic regimes. A model is being developed for application to the aspen parkland and upland forests at the limit of the boreal forest. It will also focus on producing realistic mortality responses (including embolism and possibly non-structural carbohydrate exhaustion). For aspen, a shrub layer will be included, and clonal differences in ecophysiological responses may also be incorporated.

3. Ian Campbell:

Forest succession

A gap model for the BFTCS area will be developed with the primary aim of understanding the role of wildfire in boreal forest succession. It will be validated against analyses of the pollen and charcoal record (cores from peatlands and varved lakes) along the transect. Shorter-term responses will be tested using dendrochronology (tree ring analysis).

*ESSA Ltd., Vancouver, B.C.

PACIFIC REGION

A. Thomson:

My modelling activities have declined in recent years as I moved more into the area of Artificial Intelligence and Multimedia. My major modelling activity at present is the development of a tree object oriented graphics modelling system (TREES++). This system is the basis of a defoliation estimation tutorial system (DESTIMAS) currently under development, and is also being used as the link between forest models and remote sensing studies.

R. Alfaro:

A model (SWAT or Spruce Weevil Attack Trials) was developed to simulate the effects of spruce weevil on growth of Sitka spruce. Work is now underway to link this model with MoF TASS (Tree and Stand Simulator).

H. Barclay:

The SHAWN model has indeed undergone considerable development since the 1986 report, although it is officially dead now. However, it lives under the guise of the new carbon budget model. Although the emphasis is now on tallying carbon, it is still basically the Shawnigan model. It is now an individual tree model and incorporates the Shawnigan trees (one plot at a time) as they existed in 1970, with tabulated dbh's, heights, heights to live crown, and positions. It is still in a state of development; a water balance model is being installed as is a temperature model, both consructed last year but not yet installed. Also a decomposition model is being constructed and will be installed by the end of this semester by a COOP student. SHAWN was never designed as a predictive model, but rather as a scientific tool for testing ideas.

E. Hetherington:

HSPF (Hydrologic Simulation Program Fortran) model is now being calibrated using Carnation Creek Experimental Watershed data.

Bonnor/Dejong/Boudewyn:

Development of the STIM growth model, reported on elsewhere, has been our main task. In addition, we have undertaken the following:

a) established a research installation in the Queen Charlotte Islands, to assess the effect on growth in young sitka spruce-hemlock stands of thinning and fertilization;
b) with Holger Brix, nearly completed studies to assess the effect on coastal Douglas-fir (the Shawnigan Lake installation);
c) initiated a study of growth and stand development in uneven-aged interior Douglas-fir; and
d) through FRDA, sponsored five additional projects.

G.M. Bonnor

Working Group Business Session

FORESTRY CANADA MODELLING WORKING GROUP

Minutes of Annual General Meeting
Victoria, B.C., February 9, 1993, 8:35-10:20

Present: M. Bonnor (chair), I. Bella, C. Cieszewski, D. Price, C.-H. Ung, J. Flewelling, H. Barclay, A. Thomson, P. Boudewyn

1. Approval of agenda.

The agenda for the meeting was discussed and approved.

2. Minutes of previous meeting.

The minutes of the previous meeting (Sault Ste. Marie, Aug.23, 1991) were approved as distributed.

3. Business arising

a. **Joint modelling project** - It was agreed at the August '91 meeting that the framework of the growth model (STIM) under development at the PFC would be used as the basis for the joint modelling project. This model is now almost complete, and the main question posed at this time is, "How do we effectively transfer the STIM results to each ForCan cooperator?"

Mike Bonnor proposed that a technical workshop be held at the PFC in the near future (May 1993 ?). This workshop would explain development of all the components of the model and the problems that were encountered and solved. Suggestions were made to ensure the success of this meeting, e.g. sending material to each cooperator in advance of the meeting, preparing manuals and documentation, and ensuring that major problems in the model building process were explained. The group agreed to this meeting. A date will be announced shortly.

A second level of tech transfer exists between each region and provincial forestry agencies. Huor Ung felt that transfer at this level would be more successful if the PFC establishes a method with the BC MoF that works, and then explains this method with the other ForCan regions. Mike Bonnor agreed to this but explained that this will occur at some later date; the immediate task is to focus on the process of transferring STIM to each region.

b. **Communications** - The electronic bulletin board appears not to be used very much even though it is a good tool for general uses such as meeting announcements. No special efforts will be made to keep it alive. Mike Bonnor will talk to Marg Penner about its future.

There was general support for the newsletter; G. Larocque is encouraged to send it out a least twice per year.

4. Other business.

Some concern had been expressed about the status of this Working Group - its apparent split between growth and yield modellers and other disciplines, and its support by management. Mike Bonnor assured everyone that the group has the full support of Headquarters. Everyone agreed that the group should continue to function as before, and to include and encourage modellers from all disciplines to play an integral part.

5. Next Meeting.

The next meeting will be held in Quebec City, November 17-19, 1993. Huor Ung is arranging the meeting and international conference. To date, he has received 30 proposals for presentations.

The proposed schedule is as follows:

Wednesday 17 - ForCan modelling working group meeting.
Thursday 18, Friday 19 - International workshop with presentations.

The proceedings will be published **before** the conference. The expected attendance is about 250 people.

P. Boudewyn
Recorder

Field Trip

SHAWNIGAN LAKE INSTALLATION

Core Study

Objectives

To measure the growth response of Douglas-fir stands to thinning and nitrogen fertilization.

To provide a baseline of information for related multidisciplinary studies.

Stand History

Wildfire in 1925, salvage logged, reburned in 1942, then planted in 1948 with 2 yr old stock. Heavy natural regen from 1945 cone crop. Experiment established in 1970.

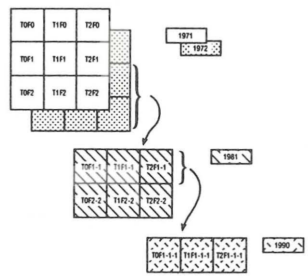
Location: Shawnigan Lake, B.C.
Current Age: 45 yrs (1993)
SI (Bruce): 25m @ 50yrs BH
BEC: CWHxm

Plot size: 0.0405 ha
Buffer: 15 m treated buffer

Forestry Canada   Forêts Canada

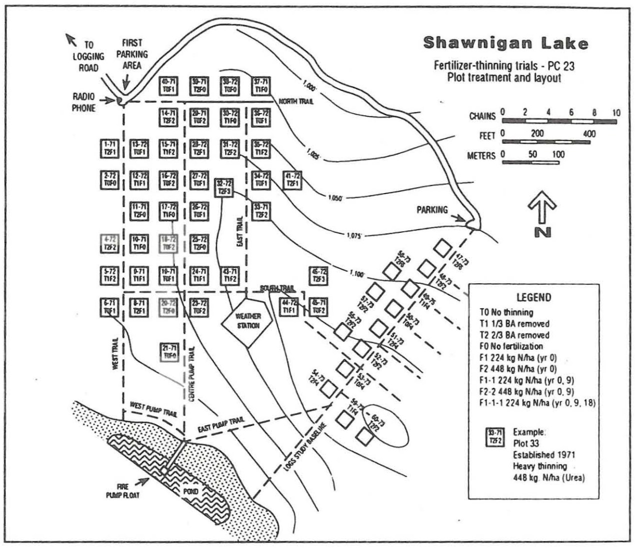
Main experiment

Three thinning and fertilization levels, replicated twice over two years. Refertilization to a subset of plots 9 & 18 years after initial treatment.

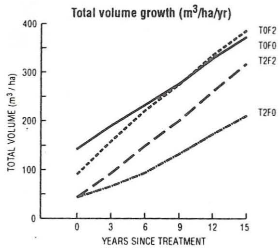


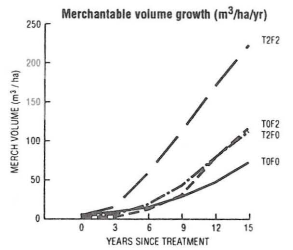
PLOT CHARACTERISTICS @ ESTABLISHMENT

Treat-ment	Trees (#/ha)	DBHq (cm)	BA (m^2/ha)
T0	4250	7.8	23.1
T1-ini	3911	8.2	22.4
T1-res	1923	9.4	14.5
T2-ini	3854	8.1	21.9
T2-res	914	10.5	8.3



Results up to 15 years following treatment

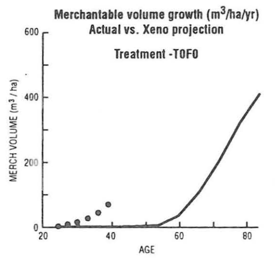


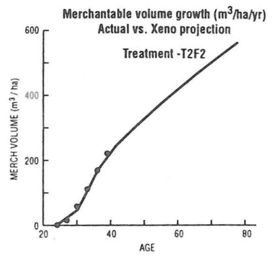


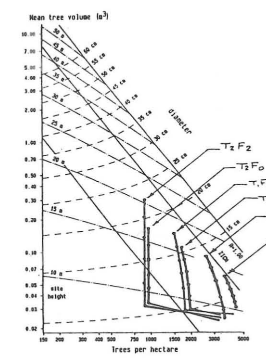
Adjusted means from analyses of covariance 15 years after treatment (Gardner, 1990)

Treatment	Quadratic Mean Diameter Core Trees	Quadratic Mean Diameter Crop 250	Quadratic Mean Diameter Crop 500	Average Height	Basal Area	Total Volume Core Trees	Total Volume Crop 250	Total Volume Crop 500	Merch Volume 12.5 cm Limit	Merch Volume 17.5 cm Limit	Individual Tree Vol Core Trees
	cm			m	m^2/ha	m^3/ha			m^3/ha		m
T0F0	12.6	20.3	18.3	13.3	46.1	356	72	113	179	81	0.1006
T0F1	13.2	21.6	19.5	15.6	46.2	387	82	131	205	107	0.1182
T0F1-1	14.4	21.8	19.9	17.0	48.9	442	83	133	257	150	0.1502
T0F2	16.3	23.1	21.2	16.7	46.3	414	107	183	234	153	0.1839
T0F2-2	16.0	24.1	22.0	17.6	50.8	456	119	192	275	201	0.1892
T1F0	15.6	20.9	19.3	15.7	35.1	294	76	128	185	113	0.1659
T1F1	16.7	22.8	21.2	16.6	38.7	346	101	171	211	162	0.1955
T1F1-1	17.0	23.2	21.4	17.9	43.0	390	102	167	254	189	0.1999
T1F2	17.6	23.7	22.1	17.3	44.5	394	107	187	260	199	0.2236
T1F2-2	17.7	25.1	22.9	18.7	47.1	458	131	211	310	228	0.2325
T2F0	18.9	23.3	21.7	17.0	25.2	221	102	174	150	111	0.2423
T2F1	20.4	25.3	23.7	19.1	30.0	286	126	220	203	188	0.3149
T2F1-1	21.7	26.2	24.5	19.4	32.1	320	142	245	228	217	0.3644
T2F2	22.1	26.8	25.3	19.7	35.7	339	139	242	237	234	0.3633
T2F2-2	23.3	27.2	25.9	20.2	35.9	348	149	265	261	257	0.4129

Comparison with forest growth models







The Density Management Diagram for coastal Douglas-fir (after Drew and Flewelling 1979).

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