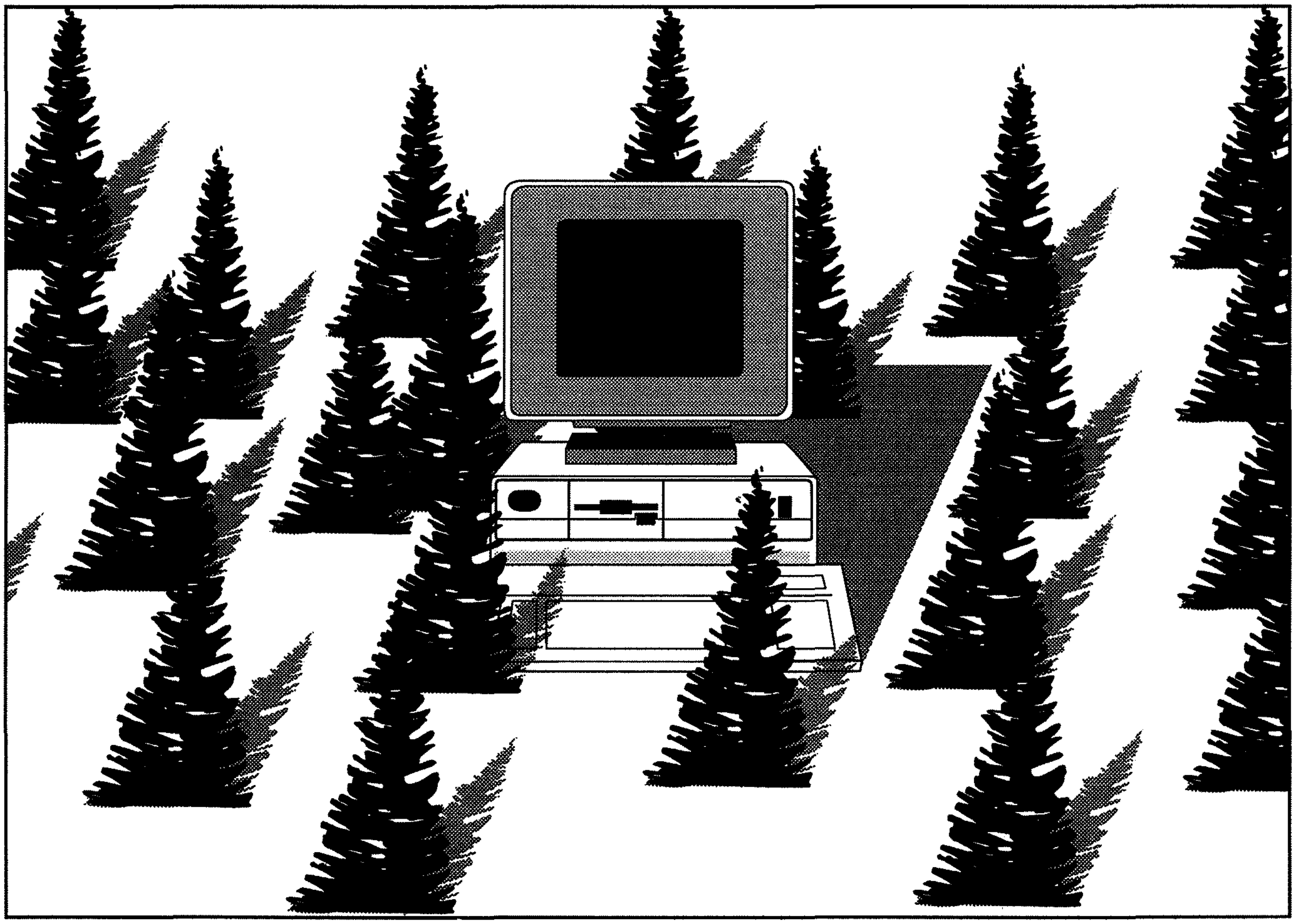
Forestry Canada
Modeling Working Group

Proceedings of the fifth modeling workshop

H. Grewal, compiler
Northwest Region



Forestry Canada · Forêts Canada

FORESTRY CANADA MODELING WORKING GROUP

Proceedings of the fifth annual workshop
Kananaskis Centre for Environmental Research
December 13-14, 1990

H. Grewal[1], *compiler*

FORESTRY CANADA
NORTHWEST REGION
NORTHERN FORESTRY CENTRE
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The papers presented here are published as they were submitted with only technical editing and standardization of style. The opinions of the authors do not necessarily reflect the views of Forestry Canada.

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ABSTRACT

A workshop dealing with modeling in forestry was held December 13-14, 1990 at the Kananaskis Centre, University of Calgary, Kananaskis, Alberta. A total of 22 participants including 3 invited outside guests were present. This volume contains most of the papers presented at the workshop, as well as poster abstracts presented. Subjects include modeling in a wide spectrum of specialities within forestry. Minutes of the business meeting of Forestry Canada Modeling Working Group and some regional reports are also included.

RÉSUMÉ

Un atelier portant sur la modélisation en foresterie s'est déroulé les 13 et 14 décembre 1990 au Centre Kananaskis de l'Université de Calgary, à Kananaskis, en Alberta. Au total, 22 participants, dont 3 invités de l'extérieur, y ont participé. Cet ouvrage renferme la plupart des articles présentés lors de l'atelier ainsi que des résumés des affiches. Parmi les sujets abordés, mentionnons la modélisation dans un grand nombre de spécialités englobées par la foresterie. Le compte rendu de la séance de travail du groupe d'étude de la modélisation de Forêts Canada et certains rapports régionaux sont également présentés.

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WORKING GROUP BUSINESS SESSION

FOREWORD

The Fifth Forestry Canada Modelling Workshop was held at the Kananaskis Centre, University of Calgary, Kananaskis, Alberta on December 13-14, 1990. These modelling workshops serve also as the annual meeting of Forestry Canada Modelling Working Group. Previous workshops were held in Forestry Canada HQ, Ottawa (1985); Pacific Forestry Centre, Victoria (1986); Petawawa National Forestry Institute, Chalk River (1987); and Maritimes Forestry Centre, Fredericton (1989).

This volume contains most of the papers that were presented at the workshop, as submitted by the authors, as well as abstracts of posters presented. The Thursday (13th) morning modelling session was moderated by Bijan Payandeh, while the afternoon session was moderated by Mike Apps.

On Friday morning (14th December) posters were presented along with model and software demonstrations. A total of five posters and a host of models were presented.

A working group business meeting took place on late Friday morning. Topic discussed include updates on modelling activities in the various Forestry Canada establishments, and plans for the next workshop - scheduled for August 1991 in Sault Ste. Marie, Ontario. A summary of the business meeting prepared by Jim Richardson is included. Bijan Payandeh provided a summary of modelling activities in the Ontario Region. Mike Bonnor presented a summary of activities at Pacific Forestry Centre. Pierre Bernier provided a synopsis of Laurentian activities. A description of the timber supply modelling project at Maritimes Forestry Centre was provided by Ken Runyon. A list of the workshop participants is also included.

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LOGPLAN Resurrected

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ABSTRACT

LOGPLAN, a computerized planning model, was developed in the 1970s as an aid to the forest manager in developing a one-year logging operations plan. Given the resources of available wood and equipment, it minimized the cost of satisfying mill demands. Recent modifications to the model are described, the most significant being the inclusion of regeneration activities in the operating system being analysed. The method of preparing the system flowchart and the input data is illustrated using the Hypothetical Forest Company as an example.

INTRODUCTION

The original LOGPLAN model was developed at the Forest Management Institute in Ottawa during the mid-1970s (Newnham 1975). It was designed as an aid to the Forest Manager in preparing his one-year logging operations plan. Given the resources of available wood and of available logging equipment, LOGPLAN optimized equipment utilization (scheduling) in such a way that the cost of supplying mills with a known volume of wood -- the mill demand -- was minimized, subject to a number of constraints imposed on the logging system by the user.

The model was tested on a number of company operations (see Newnham 1976 for an example), some of which were quite extensive (Figure 1), and proved to be quite adaptable. However, with this field experience, a number of modifications and additions were made. These included the option of identifying groups of "sorting" activities and of placing a restriction on the maximum volume of wood that could be held in a specified group of stores, instead of the individual stores. Response from the company staff who cooperated on the project was quite enthusiastic -- so why wasn't LOGPLAN accepted and implemented by the companies?

At that time, there were probably three reasons: a lack of "computer-literate staff", management resistance to trying something "new", and only limited access to the main-frame computers and linear programming (LP) software required to perform analyses. As one woodlands manager later remarked: "LOGPLAN was five years ahead of its time!" With the advent of a new generation of computer-literate forestry graduates, a management that is more receptive to computer-based technology, and the general availability of personal computers and workstations that are as powerful as the main-frames of the 1970s, most of these roadblocks have been overcome.

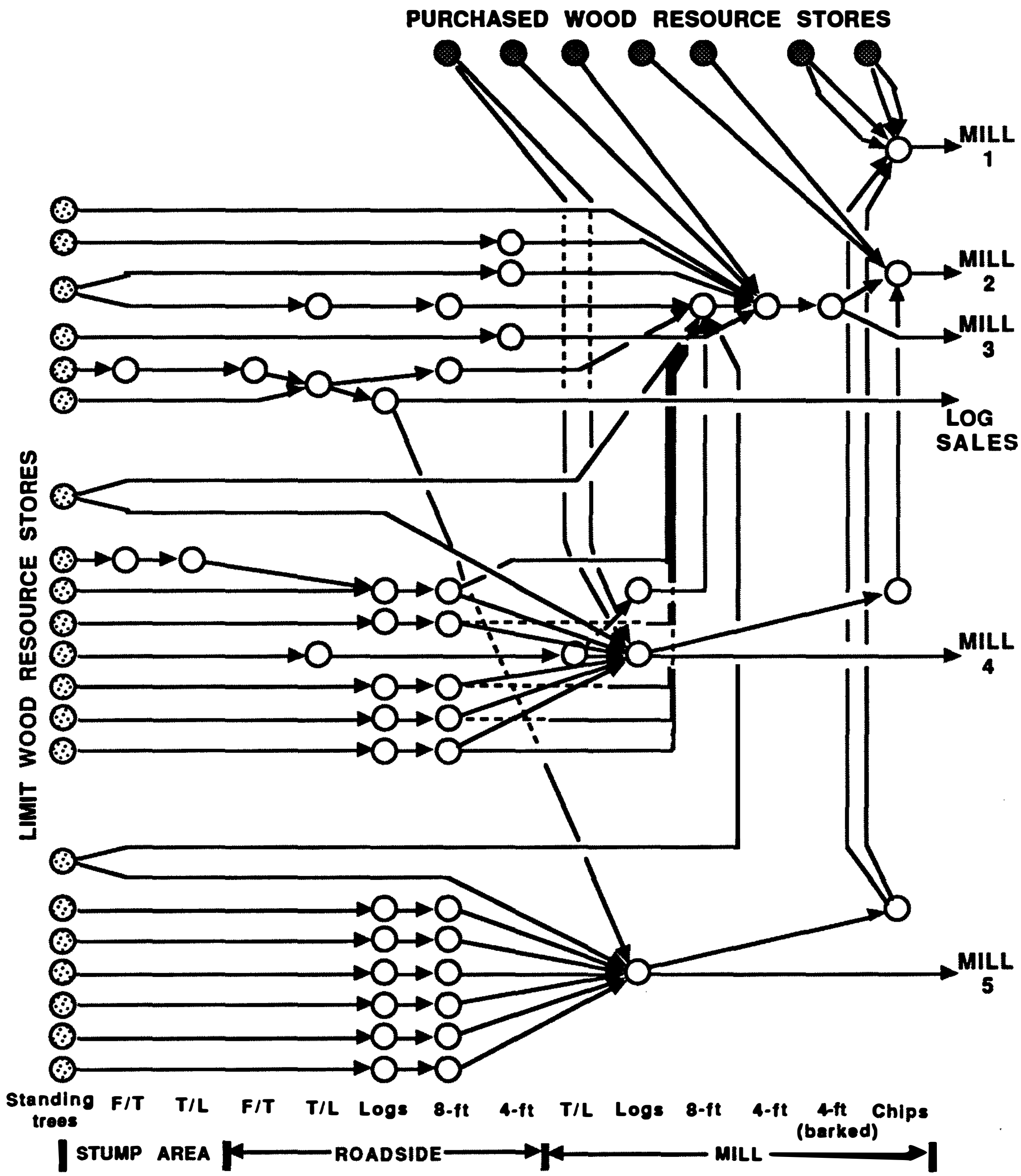

Figure 1. Flow chart of the harvesting operations of an eastern Canadian forestry company

Besides advances in computing technology and changes in management attitudes, the 1980s also brought changes in forest management. In most provinces, the companies have now taken over the responsibility for regenerating areas that they harvest. It would, therefore, seem logical to include these regeneration activities in any model used to minimize the cost of meeting a mill's wood requirements.

It must be emphasized that LOGPLAN is a planning "tool" and does not provide definitive answers to planning problems. Rather, it should be used to provide answers to "What if ...?" questions, with the manager retaining the responsibility for the final choice of plan.

USING LOGPLAN

The modifications and additions outlined previously have been incorporated in the revised model, called LOGPLAN II. In addition, extensive changes have been made to the method of data input and reporting in an attempt to make the model easier to use. The LP optimization is now performed with the proprietary software, XMP (XMP Software Inc. 1989).

The procedure for using LOGPLAN to conduct an analysis is as follows:

(1) Construct a flowchart of the company's harvesting, regeneration, and wood delivery operations.

(2) Convert the flowchart model to a form understood by the computer by entering input data for the system parameters, operating periods, stores, machines, and harvesting and regeneration activities.

(3) Correct any input errors on the input summary files.

The remaining steps are done automatically by running different programs:

(4) Generate the LP matrix.

(5) Obtain an optimum solution using XMP.

(6) Prepare reports from XMP output.

The Harvesting Operations Flowchart

The flowchart for the Hypothetical Forest Company shown in Figure 2 was designed to show as many as possible of the special features of LOGPLAN II. "Stores" are shown as circles and "activities", whose main function is to transfer wood from one store to the next in the system, are shown as arrows.

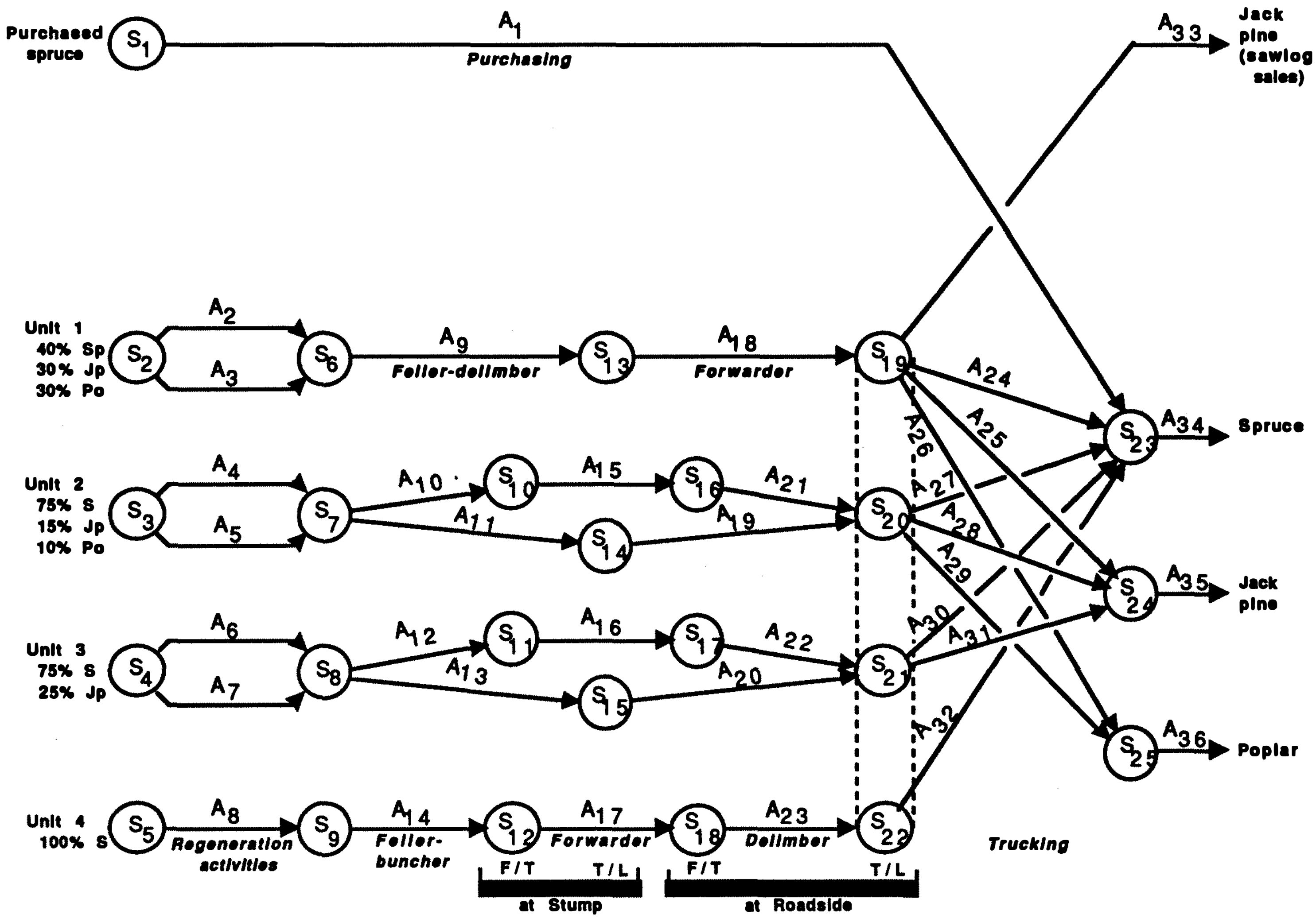

Figure 2. LOGPLAN flow chart for Hypothetical Forest Company

Wood resource stores, consisting of a single source of purchased wood (S_1) and four harvesting units (S_2 - S_5) are shown on the left of the chart. Mill blockpiles (S_{23} - S_{25}), from which the mill demands (activities A_{34} - A_{36}) are met, are shown on the right. The following rules apply to the numbering of stores:

(1) Stores of purchased wood (if any) are numbered first.

(2) Other wood resource store, the harvesting units, are numbered second.

(3) Mill blockpiles are numbered last.

(4) Intermediate stores may be numbered in any order but it is usual to number them in sequence from left to right.

A harvesting unit consists of a collection of stands that have been scheduled for harvesting (or as candidates for harvesting) in the forest management plan. Within a unit, the stands are similar in species composition, age, and site quality, and are in the same area (although units may overlap). Topography, trafficability, and distance to the mill are other factors that may be taken into account in composing these units.

The rules for numbering activities are similar to those for numbering stores:

(1) Wood-purchasing activities (if any) are numbered first).

(2) Activities emptying the other wood resource stores (harvesting units) are numbered second.

(3) Mill demands are numbered last.

(4) Wood-selling activities (if any) are numbered immediately before the mill demands.

(5) Other activities are usually numbered in sequence from left to right.

Regeneration activities (A_2 - A_8), if present, always "empty" the store that they are responsible for regenerating and each "fills" a dummy store (S_6 -S_9) with zero capacity. This ensures that any stores that are harvested are regenerated. Although in the flowchart it appears that regeneration takes place before harvesting, in practice, it is usually confined to the planting season and takes place as long as a year (or more) after harvesting.

In Figure 2, certain activities are grouped to form "activity groups". Activities A_9, A_{11}, and A_{13} all use feller-delimbers while A_{10}, A_{12}, and A_{14} use feller-bunchers. Forwarders are used in A_{15} -A_{20} but, in the first three of these, full trees are being transported while in the remainder it is tree lengths. Because the corresponding load sizes will be different, production rates will have to be adjusted accordingly. Activities A_{24} -A_{32} are responsible for trucking wood to the mill blockpiles but are, at the same time, "sorting" activities that ensure that wood leaving stores S_{19} - S_{22} is in the proportions indicated in the corresponding harvesting unit. There is some flexibility in directing wood from S_{19} to the mill or sawlog sales but the combined proportion must equal 30 per cent of the total production of the four activities emptying S_{19}. Stores S_{19} - S_{22} form a "store group" for which a maximum total inventory is specified.

Data Input

Initial data input is done interactively in response to "prompts" on the terminal screen. Examples of some of the more important input follow.

General System Parameters.

For the Hypothetical Forest Company, these are shown in Table 1.

Table 1. System parameters and their values for the Hypothetical Forest Company

Description of system parameter	Value
Number of years in plan (max. = 5)	2
Number of operating periods per year (max. = 20*)	4
Total number of stores (max. = 50*)	25
Number of purchased-wood stores (max. = 10)	1
Number of management unit stores (max. = 8*)	4
Number of groups of stores (max. = 10)	1
Total number of activities (max. = 60*)	36
Number of wood-purchasing activities (max. = 60*)	1
Number of wood-selling activities (max. = 60*)	1
Number of activity groups (max. = 10)	6
Number of mill demands (max. = 10)	3
Number of groups of sorting activities (max. = 10)	3
Number of regeneration machine types (max. = 10)	3
Number of harvesting machine types (max. = 10)	4
Number of truck types (max. = 10)	1
Number of planting-stock constraints (max. = 10)	1
Annual silvicultural (regeneration) budget ($)	2000000

* These values may be changed by changing the PARAMETER statements in the FORTRAN programs.

Although LOGPLAN II is usually used to develop a one-year operating plan, it is often advisable to run the model for one or two extra years to ensure that the current year's plan will not adversely affect operations in subsequent years. Each year is divided into a number of operating periods that generally correspond to the seasons. Within each period, the production rates for each type of machine are assumed to be constant. For the first year, the user is asked to enter the starting and finishing dates for each period, and the number of operating days within the period.

Stores

Examples of the data requested for a harvesting unit store and an intermediate store are given in Figures 3 and 4. For all wood resource stores (whether harvesting units or purchased wood), the difference between the initial and final inventories **must** be harvested during the planning period. The "daily inventory charge" for intermediate stores (and also mill blockpiles) is an allowance for interest on the capital value of the wood held in those stores and for any maintenance charges associated with the storage area.

```
Store No.  3  Description (Max. = 24 characters):
              >Harvesting Unit 2
               Initial inventory (m**3):          280000
               Maximum final inventory (m**3):    100000
               Area (ha): 1350
               Average number of trees/m**3: 8.0
```

Figure 3. An example of the input data required for a harvesting unit store.

```
Store No. 16  Description (Max. = 24 characters):
              >F/T at roadside
               Initial inventory (m**3):                0
               Maximum inventory (m**3):              500
               Maximum final inventory (m**3):          0
               Daily inventory charge ($/m**3):     0.006
```

Figure 4. An example of the data input for an intermediate store.

If there is no limit on the maximum volume of wood allowed in a store, a value of -999 is entered for maximum inventory. If it is desired to have a fixed volume of wood in a store at the end of the planning period, the negative of that value is entered for the maximum final inventory.

Machines

There are three basic types of machine: those required for harvesting (including skidding or forwarding, slashing, etc.), for regeneration, and for trucking. An example of the data required for a harvesting machine type is given in Figure 5.

Variations in production rate for a machine with season, tree size or site are accommodated by means of Productivity Adjustment Factors (PAFs). These have default values of 1.00 but the user has the option of changing any if he so wishes. Thus a value of 0.95 for period 2 would indicate that the production rate would be five per cent below the standard for that machine during that period.

```
Harvesting machine type  3
Description (Max. = 24 characters):
           >Forwarders
Number of units available: 7

For the next four entries on cost, you may either enter
     values for Capital, Fixed and Variable costs in
     $/shift OR a single value in $/m**3 (in which case
     enter 0 for each of the three shift costs).

Capital cost ($/shift): 240

Fixed cost ($/shift): 320

Variable cost ($/shift): 200

Production (m**3/shift): 135
```

Figure 5. An example of the input data required for a harvesting machine type.

Activities

An example of the input data required for activity A_{18} is given in Figure 6.

```
Activity No.  18 Function (1 letter upper or lower
case): h

 FMU store from which wood originated: 2
 Description (24 characters): Forwarder (T/L)
 Productivity adjustment factor (e.g. 1.05): 1.20
 Machine type No.: 3

 Number of machine-shifts available in each period
     (for purchasing, selling, and mill demand
     activities, write "1")

Are the number of machine-shifts constant for all
     periods [Y/N]? y
Number of available machine-shifts per day: 14
No. of store being emptied: 13
No. of store being filled: 19
```

Figure 6. An example of the input data required for an activity.

The function "h" indicates that it is a harvesting activity that uses harvesting machine type 3.The FMU store is the harvesting unit in which the wood was harvested. It is required so that any adjustments in production rates due to tree size can be implemented. The activity PAF is used to adjust production rates for this activity only. Machine type 3 is a forwarder for which the production rate was specified for full trees. In A_{18}, it is being used for tree lengths and so, because the load is larger, production has been increased by 20 per cent. If the number of machine-shifts had not been constant for each period, the user would have been prompted to enter the appropriate numbers for each period. The numbers of the stores being emptied and filled are required to indicate to the model where the activity fits in the system.

Planting Stock Constraints

Besides setting a constraint on the annual budget for silviculture or regeneration, it is also possible to limit the number of plants that are available each year for each type of planting stock. An example of the input data that are required for this is given in Figure 7.

```
Stock type 1  Description:
             >Container plants

Total available stock: 2000000
Number of regeneration activities using this stock: 3
            1 Activity: 3
            2 Activity: 5
            3 Activity: 7
```

Figure 7. An example of the input data required for planting stock constraints.

Input Data Correction

The program responsible for the interactive data input generates a number of input summary files that are, in turn, used as input to the matrix generator. The files show the input data in readily understood tables (an example is given in Figure 8). Input errors can be easily corrected using a text editor. Also, if a number of different scenarios are to be tested on the same basic system, the necessary changes can be made to these files without having to repeat the rather time-consuming interactive input.

Matrix Generation

The matrix generator calculates the cost elements in the objective function:

$$\text{minimize } Z = c_{11}x_{11} + c_{12}x_{12} + \ldots + c_{21}x_{21} + \ldots + c_{nm}x_{nm}$$

where:

c_{ij} = the cost in $\$/m^3$ for activity A_i in period j,
x_{ij} = the production in m^3 of A_i in period j,
n = the number of activities(not including mill demands),
and m = the number of operating periods.

The values of the c_{ij} include an allowance for the inventory charges in the stores being emptied and filled by A_j. For regeneration activities, where production and cost are expressed on a per ha basis, these are converted to the m^3 equivalent.

The formulae for the constraints range from the simple to the very complex and will not be detailed here. Broadly, they ensure that:

(1) The production of each activity in each period does not exceed the maximum potential production for that period;

(2) The inventory in each store never becomes negative or exceeds its maximum capacity;

(3) For each wood resource store, the inventory is reduced to at least the specified maximum final inventory;

(4) For each activity group, the number of machines scheduled to operate in each period never exceeds the number available;

(5) For each store group, the specified group maximum inventory is never exceeded;

(6) For each group of sorting activities, the proportional production of each activity falls within the specified ranges for the group;

(7) The silvicultural budget is not exceeded in any year;

(8) Limits on available planting stock are not exceeded in any year; and,

(9) Mill demands are met exactly as specified.

If any of these constraints are violated, there is no feasible solution for the given input data. When this happens, the input data must be revised (e.g. resources increased or demands reduced) and the model rerun.

LP Optimization

For LOGPLAN II, the LP optimization is done using the XMP software. This accepts output from the matrix generator in standard MPSX format (International Business Machines 1972) so that any software that accepts this standard could be used. A solution can be obtained for the Hypothetical Forest Company in about three minutes on a SUN Workstation.

Output Reports

Output of the solution from XMP is converted by the computer to a form that is easily understood by the forest manager. It consists of a number of tables that show, for example, the production of each activity in each period and the number of machines required to obtain that production, the inventory of each store at the end of each period, the area regenerated by each method and the number of plants that are required. Two of the more important tables are shown in Tables 2 and 3.

Table 2 gives a summary of the production and costs broken down into components. The model includes the option of discounting cost and revenues to the present but, for planning periods of one or two years, this is usually not necessary. Table 3 shows the total production and machine utilization for each activity group. This can indicate possible constraints to lowering the cost of wood supply to the mills. In the present example it appears that the feller-delimbers are a bottleneck, as they are 100 per cent utilized throughout the planning period. Feller-bunchers, on the other hand, only utilized for about 75 per cent of the time so that exchanging one or more feller-bunchers for a feller-delimber could result in a reduction in cost. Changes could be quickly made to the summary input files and the model rerun to see if this strategy does in fact reduce the overall cost.

CONCLUSION

This paper has shown how the harvesting, regeneration, and wood delivery operations of a company may be studied using the LOGPLAN II model.

How can LOGPLAN II help the forest manager? Given a flexible attitude and a good database, LOGPLAN can provide the following assistance in minimizing the cost of harvesting and regeneration while satisfying mill demands:

(1) It can give an estimate of this cost for the planning period that can be used as a basis for budgeting.

(2) For each type of machine and for each operating period, it can indicate the activities in which the machines will be operating, the minimum number of machines that will be required, and the number of machine-shifts that will be operated.

(3) If the activities in which each type of machine can operate are "grouped", the percentage utilization is calculated. A value much less than 100 per cent would indicate that fewer machines are required for the group. Conversely, a value of 100 per cent would indicate that having more machines available might lower costs.

(4) For each activity, the scheduled production is given for each period.

(5) For each regeneration method, the number of plants used is given. This can help in planning nursery production.

Job No. 1 Run No. 1

V O L U M E   A N D   C O S T   S U M M A R Y

	Discounted costs and revenues			Actual costs and revenues		
	Volume m**3	Value ($)	($/m**3)	Volume m**3	Value ($)	($/m**3)
Capital cost*		4734400.00	6.022		4734400.00	6.022
Operating costs:						
Logging**	786190	11862992.00	15.089	786190	11862992.00	15.089
Inventory***		4682.95	0.006		4682.95	0.006
Sub-total	786190	11867675.00	15.095	786190	11867675.00	15.095
Regeneration	4094~	3089375.00	3.930	4094~	3089375.00	3.930
Limit-wood total	786190	19691450.00	25.047	786190	19691450.00	25.047
Purchased wood	300000	9600000.00	32.000	300000	9600000.00	32.000
Total production	1086190	29291450.00	26.967	1086190	29291450.00	26.967
Less sales	19190	786790.00	41.000	19190	786790.00	41.000
Total mill supply	1067000	28504660.00	26.715	1067000	28504660.00	26.715

~ Area harvested and regenerated in ha

* Interest on capital invested in machines plus depreciation. This item is charged against each machine regardless or not of whether it is scheduled for operation. The cost in $/m**3 is obtained by dividing the total capital cost by the volume of wood produced on limits

** Does not include interest on capital

*** Inventory cost in $/m**3 is obtained by dividing the total inventory cost by the volume of limit wood. The charge is applied to limit wood only

Interest rate for discounting = 0.000% per year

TABLE 2: Hypothetical Forestry Company: summary of production and cost

Job No. 1 Run No. 1

ACTIVITY GROUP PRODUCTION

Group No.	Description:	Total Prodn. (*)	Production (*) in period: 1	2	3	4	5	6	7	8
1	Slashburn: nat. regen.	1760	160	360	160	200	160	360	160	200
		(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
2	Feller-bunchers	437796	34691	103120	39939	55500	15975	96616	38975	52981
		(76.7)	(76.5)	(78.5)	(79.2)	(88.1)	(35.2)	(79.5)	(79.7)	(86.1)
3	Feller-delimbers	325624	25789	72215	28102	37140	25500	72215	28102	36561
		(100.0)	(100.0)	(100.0)	(100.0)	(100.0)	(100.0)	(100.0)	(100.0)	(100.0)
4	Forwarders	763420	60480	175335	68040	92640	41475	168831	67076	89541
		(89.4)	(100.0)	(88.7)	(100.0)	(89.5)	(68.6)	(86.0)	(100.0)	(87.9)
5	Delimbers	437796	34691	101620	41439	54000	17475	95116	40475	52981
		(92.1)	(80.3)	(100.0)	(96.0)	(100.0)	(40.5)	(100.0)	(96.0)	(100.0)
6	Tree-length trucks	754230	66070	172635	67940	87960	40875	164231	66976	87541
		(69.0)	(70.3)	(73.7)	(65.4)	(67.3)	(43.5)	(76.8)	(68.8)	(70.6)

* ha for regeneration groups; m**3 for other groups.
(values in parentheses are percent utilization of the machines assigned to the group)

TABLE 3: Hypothetical Forestry Company: production and utilization by activity group

(6) For each store, the inventory at the end of each period is given. This can also help in identifying bottlenecks in the system.

By far the greatest value of LOGPLAN II is in testing different planning strategies (asking the "What if ...?" questions). Once a model of a company's operations has been developed, a variety of scenarios may be tested rapidly and on short notice. For example, it could test the impact of a supply of purchased wood becoming unavailable (or increasing in cost). LOGPLAN could indicate the additional resources required to replace the lost supply with wood produced on company limits. The impact of changes in mill demand, due to changing market s or a strike, could also be assessed and the harvesting operations modified in anticipation of such events.

LOGPLAN has evolved over a period of 15 years and will continue to evolve. With further field testing, requests for new options or constraints will doubtless be made and, where practical, built into the model. Advances in computer hardware and software technology may also lead to improvements. However, even in its present form, LOGPLAN II can be a valuable aid to the forest manager in preparing operating plans.

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An Ecophysiological Whole Tree Approach to Modelling Tree Growth

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Forest growth has been modelled at a variety of spatial and temporal scales, from global models estimating the carbon budget of biomes to whole tree models simulating the carbon budgets of individual leaves. While these scales vary across several orders of magnitude, there are fundamental growth processes which are common across scales. These include light interception at the leaf or canopy level, the production and distribution of carbohydrates through various plant or ecosystem components, and the simulation of respiratory losses and accrual of biomass in various components. This paper will reviews the current state of ECOPHYS, an ecophysiological process-oriented approach to modelling tree growth, and addresses some of the theoretical considerations of model development and use.

We have recently completed the distribution version of ECOPHYS, an explanatory ecophysiological whole-tree process model that simulates the growth of *Populus* during the establishment year. ECOPHYS was developed as part of the USDA Forest Service North Central Forest Experiment Station's research program on Intensively Cultured Plantations for Fiber and Energy Production, funded cooperatively through the Department of Energy. The model represents a synthesis of the large body of research information developed on poplar at the NCFES Forestry Sciences Laboratory in Rhinelander, WI, Michigan and Washington State Universities, and a number of other researchers across the United States and Europe.

Applications

ECOPHYS was initially developed as a tool for the genetic screening of a large number of poplar clones. By making a series of morphological and physiological measurements on test material, a clone may be parameterized for the model and the first season's growth simulated. Response variables such as height growth or biomass production can then be compared to identify clonal material that should be carried on for field trials. The simulation approach is thus intended to be a complement to field trials, and to allow a relatively rapid screening of potential breeding stock.

The model can also be used to quantify the relative importance of physiological, morphological, or phenological clonal attributes which may be subject to genetic selection. In itself, this gives a plant breeder an understanding of specific traits for selection, as opposed to selecting for an aggregate response variable such as height growth. More importantly, the model can be used to help develop a tree ideotype. A tree ideotype has been recently defined by Dickmann as "...a model tree that will produce an economic yield that approaches a maximum in a particular environment (or on a certain site), using a prescribed cultural system and assuming a well-defined end use for the harvested products" (Dickmann and Gold 1989). In short, it is an idealized tree for a particular environment. The tree ideotype represents selection goal or end product for the plant breeder. While this goal may never be fully realized in the field, the ability to select for multiple traits can result in an increase in yield beyond that obtainable through a single trait selection program.

In addition to studying effects of genetically constrained variables, ECOPHYS may also be used to simulate the growth of poplars under varying environmental conditions, such as different light or temperature regimes (Rauscher et al. 1988). Such simulations would be difficult or impossible to conduct as field experiments. The ability to change latitude or seasonal weather patterns allows determination of a growth response in different climatic regions, or under different climatic warming senarios. In this latter application, simulated weather generated by climate change models can be used as inputs to ECOPHYS to determine the influence of different climatic warming senarios on plant growth.

Lastly, this whole tree model is essentially the computer embodiment of a theory of tree growth. Information from the large body of poplar research conducted over the last several decades has been synthesized and used to develop process-level submodels. These submodels have been integrated into a single interactive package which summarizes our knowledge of tree growth. This is not to say that the model or our knowledge is perfect. The process of model development quickly brings one to the limits of knowledge. The use of models as a heuristic tool, however, is an effective means of making directed progress through a virtually limitless realm of potential experiments. The loop of model development and directed research is a highly profitable means of efficiently acquiring the specific knowledge needed to solve the tasks at hand.

Model Summary

ECOPHYS is based on experimental field studies of the morphology, physiology, and growth of *Populus euramericana* cv. 'Eugenei' (*Populus deltoides* Bartr. ex Marsh x *Populus nigra* L.) at the USDA Forest Service, Forestry Sciences Laboratory in Rhinelander, Wisconsin, USA. The model was developed for poplar grown in Short Rotation Intensive Culture (SRIC) plantations, with the assumption that moisture and nutrients are maintained at optimal levels. The simulation begins as an "initial tree" early in the growing season and ends at the bud set date. The tree is currently modelled as a single main stem; this is a valid assumption for the first year growth of many clones. The model is currently being adapted, however, to allow development of sylleptic branches, which may occur for genetic or environmental reasons.

Figure 1 presents a conceptual overview of the model structure. In ECOPHYS, the leaf acts as the principal biological unit. Hourly photosynthate production in a leaf is determined by hourly solar radiation intercepted, temperature, leaf age and clonal characteristics. Photosynthates are periodically transported to various plant growth centers based on leaf-specific transport coefficients; they are then converted to biomass and dimensional growth. As a result of this strategy, there are no inherent growth rates in ECOPHYS. All growth occurs as a result of the photosynthates produced and distributed from individual leaves.

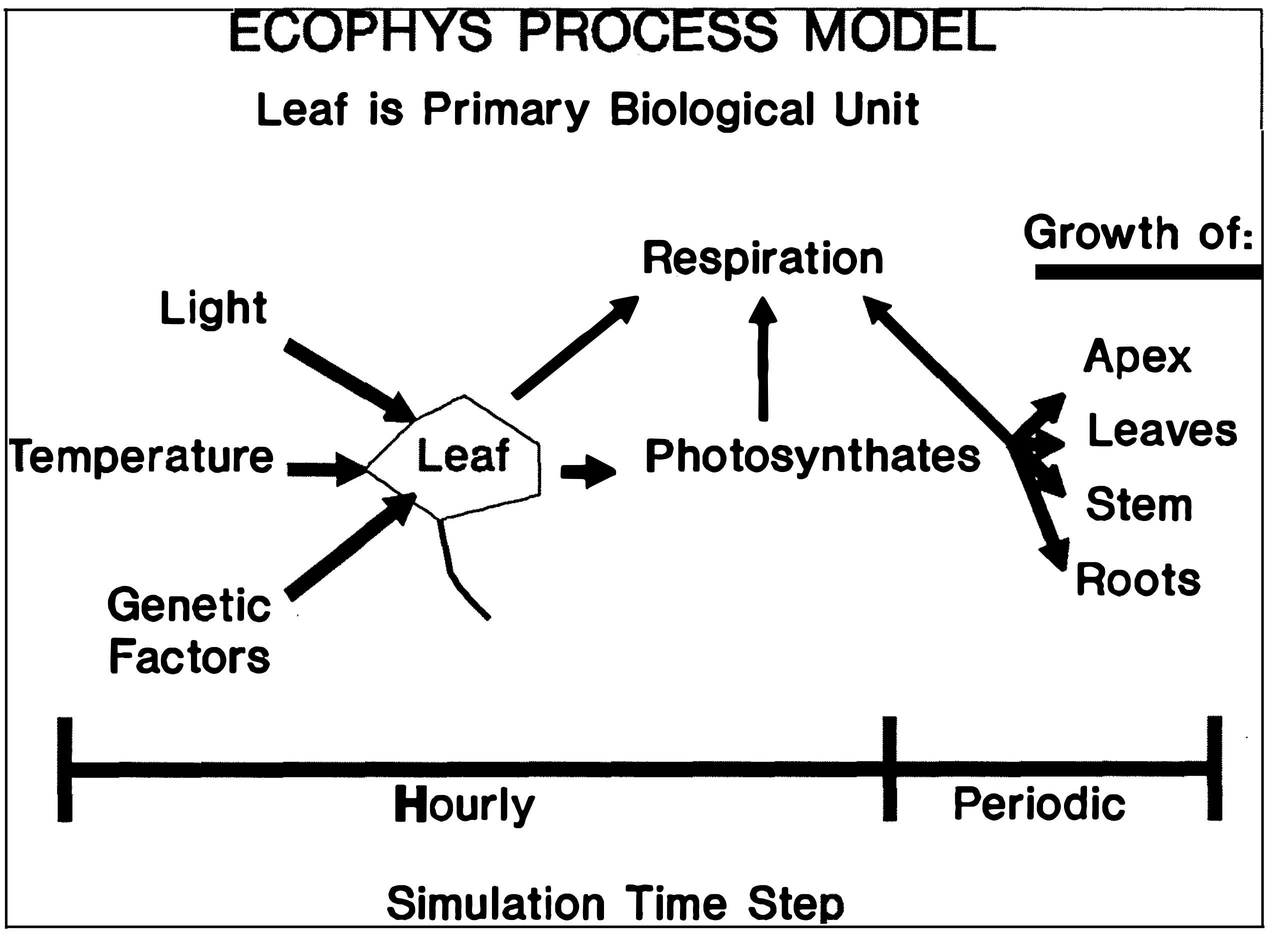

Figure 1. Conceptual overview of model.

Unique to ECOPHYS are the means by which light is intercepted by individual leaves and carbon allocated throughout the plant. Light interception is calculated, not estimated, by holding each leaf in a three dimensional coordinate system and determining interception as a function of solar altitude and azimuth and mutual leaf shading patterns for a given hour (Figure 2). This calculation-intensive approach allows a precise estimate of light interception to be supplied to the photosynthate production submodel.

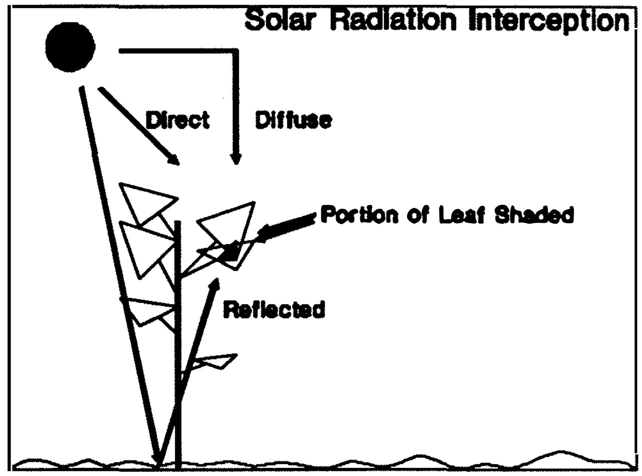

Figure 2. Light interception schematic

In the carbon allocation submodel, each leaf has a unique carbon distribution or transport pattern, determined by 14C tracer studies in controlled environments and in the field (Larson 1977, Isebrands and Nelson 1983, Dickson 1986). Photosynthate are transported upward to other leaves or stem internodes, or downward to stem internodes, the cutting, and the roots (Figure 3). Few, if any, whole-plant growth process models have incorporated such detailed photosynthate transport coefficients.

The full documentation for ECOPHYS can be found in a concept paper by Isebrands et al. (1989), the description paper by Rauscher et al. (1990), and the ECOPHYS User's Manual (Host et al. 1990). Other relevant studies are listed in the bibliography.

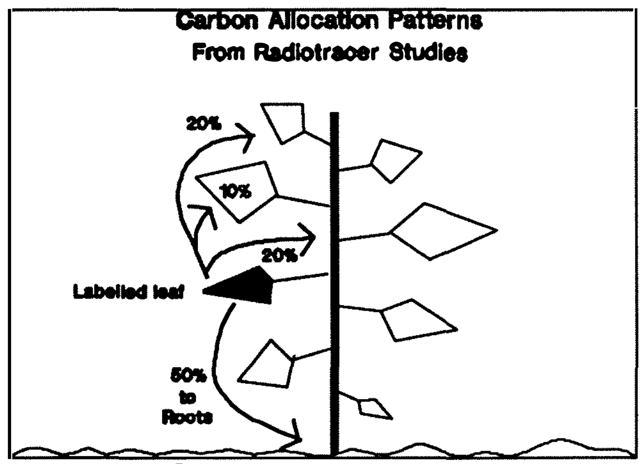

Figure 3. Carbon allocation schematic.

Theoretical vs Empirical Approaches to Model Development

In developing ECOPHYS, we have recognized a continuum of model building strategies, from empirical or statistical models to theoretical or explanatory models (Figure 4). Each type of model has its particular strengths and weaknesses and its particular place. We define empirical models are those in which the equations used do not necessarily have a biological basis, and whose coefficients arise from the curve fitting process. Empirical models work well within the range of data used to build the

Model Types
A Continuum

Model Type:	<u>Empirical</u> Correlative Statistical		<u>Process</u> Causative Mechanistic
Model Form:	No theoretical form	Form Known	Form Known
Coefficients:	Statistical Artifacts	Statistical Artifacts	Directly Measured
	Interdependent	Interdependent	Independent
Example	Allometric a,b,c	Saturating a,b,c	Saturating Fmax,E,Rd

Figure 4. Continuum of model types.

model; often they will fit the data (i.e. have a lower Mean Squared Error) better than theoretical models. Problems arise however, when the model is used to make predictions outside the range of data from which it was developed. In this case results may be unreliable and, at worst, spurious.

In the case of simulating forest growth or estimating biomass production, the use of empirical models may limit the geographic extent over which the model is applicable. The spatial limits of these models may be quantified through the use of ecologically-based land classification systems, now becoming common forest management tools in both Canada and US Forestry (Comes and Annes 1986, Host et al. 1988). When validated, cartographically-delineated changes in ecosystem type should correspond to shifts in those ecological factors (e.g. macroclimatic region, edaphic or physiographic factors) important to forest productivity. Host and Rauscher (1990) consider the use of ECOPHYS in the context of ecological land classification systems.

Intermediate along the continuum are models with a theoretical form, but whose coefficients still remain statistical artifacts of the curve fitting process. An example of this might be a power function fit to a photosynthate production data; the equation form might represent a theory of how photosynthetic rates respond to increasing light intensity, but the coefficients still lack biological meaning and cannot be directly measured.

This brings us to the theoretical end of the continuum, where there is a theoretical model form and the coefficients which drive the model are biologically meaningful and measurable variables (Figure 4). The advantage of theoretical models is that, while they be less precise at local levels, they are more applicable on a global scale, that is, they behave better outside to range of data used to develop them. In addition, the discovery of errors in theoretical models often leads to a refinement of the underlying theory, so that our knowledge of a process is increased. The photosynthate production function currently used in ECOPHYS is an example of a theoretically-based model. The equation has a rectangular hyperbolic form as proposed by Goudriaan (1982), and the three coefficients which drive it, Fmax, Pe, and Rd, have a physiological meaning and can be measured directly in field or laboratory. ECOPHYS is by no means a fully theoretical model, but as we improve our understanding of plant growth processes, we move the model toward the theoretical end of the continuum.

Chaotic vs deterministic models

In its current state, ECOPHYS is a strictly deterministic model. At certain scales, however, natural systems have been shown to exhibit chaotic behavior. Chaotic behavior is not random, but follows a unique type of mathematical order that is inherently unpredictable. A fundamental tenent of chaos is that the future state of a given system is extremely sensitive to initial conditions. In a chaotic model, any variation in initial conditions, even to the 20th decimal place, makes the output at some future time essentially unpredictable. Weather, fluid mechanics, and population life cycles have all been observed to be chaotic. James Gleik (1988) gives an accessible review of the historical development of chaos theory.

Chaos occurs as a result of feedbacks occurring between two or more interacting nonlinear equations. Since we have not included nonlinear feedbacks in ECOPHYS, chaotic behavior does not occur and the model is relatively predictable. As we continue to develop the model, however, particularly with the inclusion of nutrient dynamics, it is likely that chaotic behavior will arise. Cohen and Pastor (1991) have found that the forest growth model LINKAGES is chaotic over hundred year timespans as a result of feedback between light availability and litter quality. The important point is that if our models are accurate representations of natural processes, then the natural systems we are attempting to simulate, and, more importantly, manage, are inherently unpredictable at certain temporal and spatial scales. Recognizing the scales at which our models begin to exhibit chaotic behavior is critical toward understanding the limitations of modelling for predicting forest growth, or assessing patterns of climatic change.

Acknowledgements

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GROWTH MODELLING WITH INSUFFICIENT DATA

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Introduction

In 1986, the Pacific Forestry Centre established a "Forest Growth and Measurements" Project. We made a survey of potential clients and cooperators in the forestry community to find out what contributions we could make, how our work could fit in with existing work, what studies we should undertake. One of the more significant knowledge gaps related to interior Douglas-fir (IDF): although commercially significant, little information was available about its growth. Also, some foresters believed that growth rates could be doubled at least by proper thinning practices, leading to increased allowable annual cuts. We therefore decided to undertake an IDF study: collect available data, analyze growth rates, identify the factors influencing them, and put the results into a model framework.

We learned that Douglas-fir in the interior of BC grows mostly in uneven-aged stands. If such stands are clearcut, stand re-establishment is very difficult. Hence, partial cutting is practised. The cutting cycle is normally 20 years. In the past, the Diameter Limit harvesting method (removing all trees above a certain size) was used. A recent modification, the Fallers Selection harvesting method, also thins the residual stand. We also learned that IDF exhibits considerable variability in stand structure and growth characteristics. This variability is unexplained but likely related to moisture deficits and stand history.

We finally learned that very little permanent sample plot data exist for IDF stands. At the end of two years, we had accumulated data for only 92 plots. However, we decided to proceed with the study. The purpose of this report is to present and discuss the results.

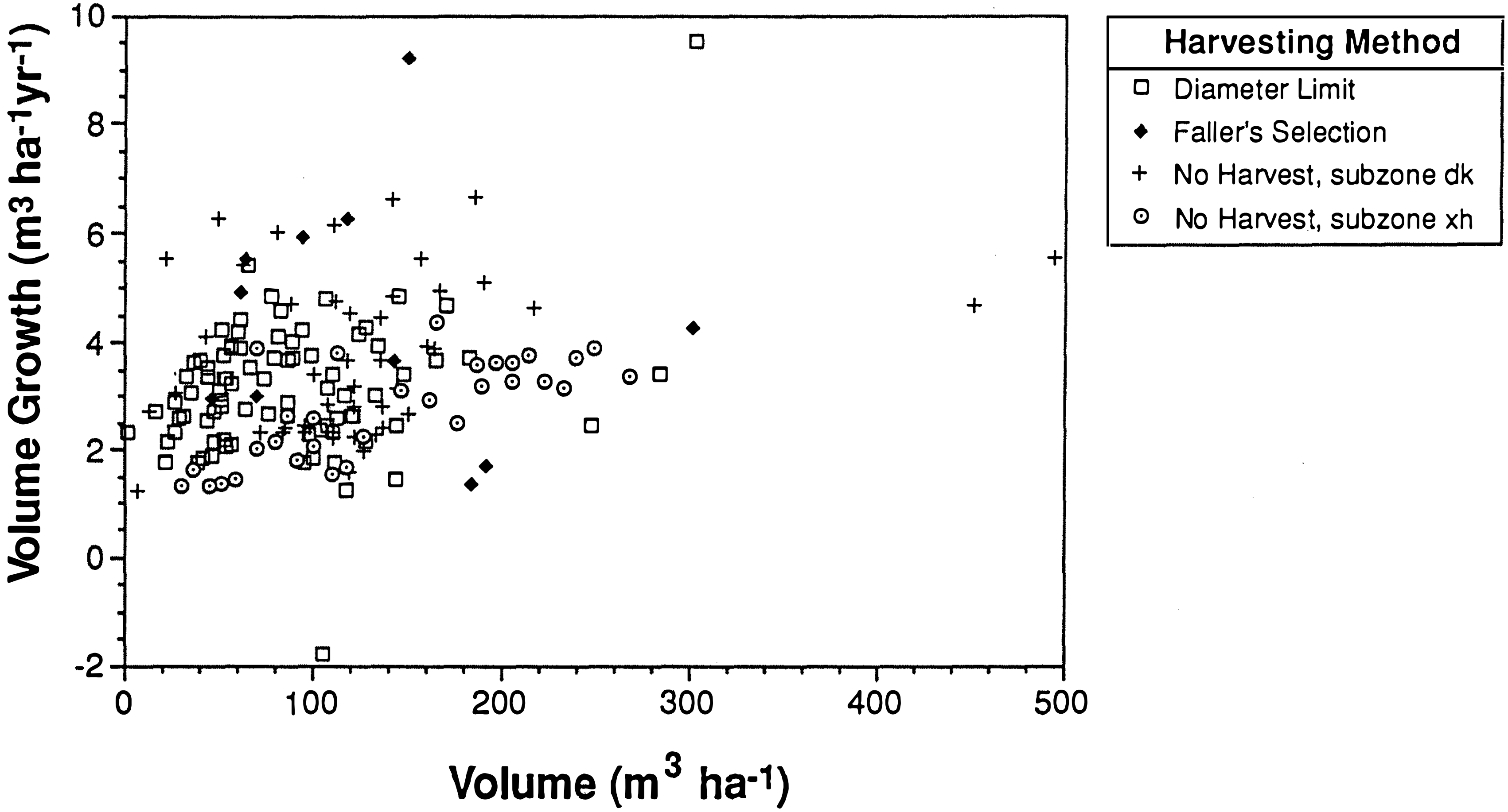
The Data Set

The data came from three sources:
1) from the provincial Ministry of Forests, data for 63 permanent sample plots, each remeasured once only, at 5-11 year intervals;
2) a set of 24 plots (the "Korol" plots) for which the growth data were obtained from increment cores. A total of 100 five-year measurement intervals were derived for these plots;
3) a set of five plots (the "Lignum" plots) for which the growth data were obtained by stem analysis. A total of 10 seven-year measurement intervals were available.

Tree heights were derived from local height-diameter equations, and mortality data from the first data set were used to estimate mortality for the other two sets.

The basic data were used to compile stand characteristics, including volume and volume growth (Figure 1) which show considerable variability: stand volume ranges up to 500 m^3ha^{-1}, while volume growth

Figure 1: Scattergram of permanent sample plot values of volume growth over volume, by harvesting method.



ranges from -1.8 to 9.5 $m^3ha^{-1}yr^{-1}$.

Analyses and Results

The following variables were included in the analyses:

Dependent : VGR = Volume growth ($m^3ha^{-1}yr^{-1}$)
Independent: TRT = Harvesting method (3 classes)
BGC = Biogeoclimatic subzone (2 classes)
TST = Time since harvest (years)
TPH = Trees per ha
BAH = Basal area (m^2ha^{-1})
QMD = Quadratic mean diameter (cm)

The first analysis was a covariance analysis, to determine if statistically significant differences existed among the classes of the two discrete variables (TRT and BGC). Results of the analysis indicated that the means (Table 1) of the three harvesting methods differed significantly, but that the BGC means within the Fallers Selection method could be combined, as could those within the Diameter Limit method. However, for the No Harvest class, BGC means differed significantly. Accordingly, four Groups (Table 1) were created from the six classes.

Table 1. Class and Group means of volume growth.

Biogeoclimatic Subzone	Harvesting Method: Fallers Selection	Diameter Limit	No Harvest
	——Volume Growth ($m^3ha^{-1}yr^{-1}$)——		
dk	5.0	3.2	3.5
xh	4.1	3.6	2.6
Grouped	4.5	3.3	3.5 2.6

The next analysis was a regression analysis to determine, for each Group, if VGR was significantly correlated with the continuous variables of TST, TPH BAH and QMD. In preparation for the analysis, scattergrams of VGR over the four variables were plotted (Figure 2).

They indicate that, in general, VGR is poorly related to TST, TPH, BAH and QMD. More specifically, the regression analysis revealed that
1) for the Fallers Selection method, none of the four variables was significantly correlated with VGR. This is at least partly due to the small sample size, only nine sets of plot data were available. As a result of this lack of correlation, the Fallers Selection method was eliminated from further study;
2) the variable TST was not significantly correlated with VGR in the other harvested Group, the Diameter Limit method.
3) the remaining three independent variables (TPH, BAH and QMD) were significantly correlated with VGR for at least some Groups, but without any consistency: no variable appeared to be superior to the other two although TPH was often equal to BAH and QMD combined .

In the end, the following equations were selected:
For the Diameter Limit method:

$$VGR = 1.35 + 0.0055TPH - 0.00000268TPH^2 \qquad R^2 = 0.28$$

For Unharvested Plots of Subzone dk:

$$VGR = -0.31 + 0.00081TPH - 0.000007TPH^2 \qquad R^2 = 0.60$$

For Unharvested Plots of Subzone xh:

$$VGR = -1.90 + 0.0015TPH - 0.183\ QMD \qquad R^2 = 0.47$$

These equations were plotted (Figure 3) together with their underlying plot values. Again, the variability of the plots is shown to be large and the lack of clear trends is obvious.

Figure 2: Scattergrams of stand variables used in regression analyses, by harvesting method.

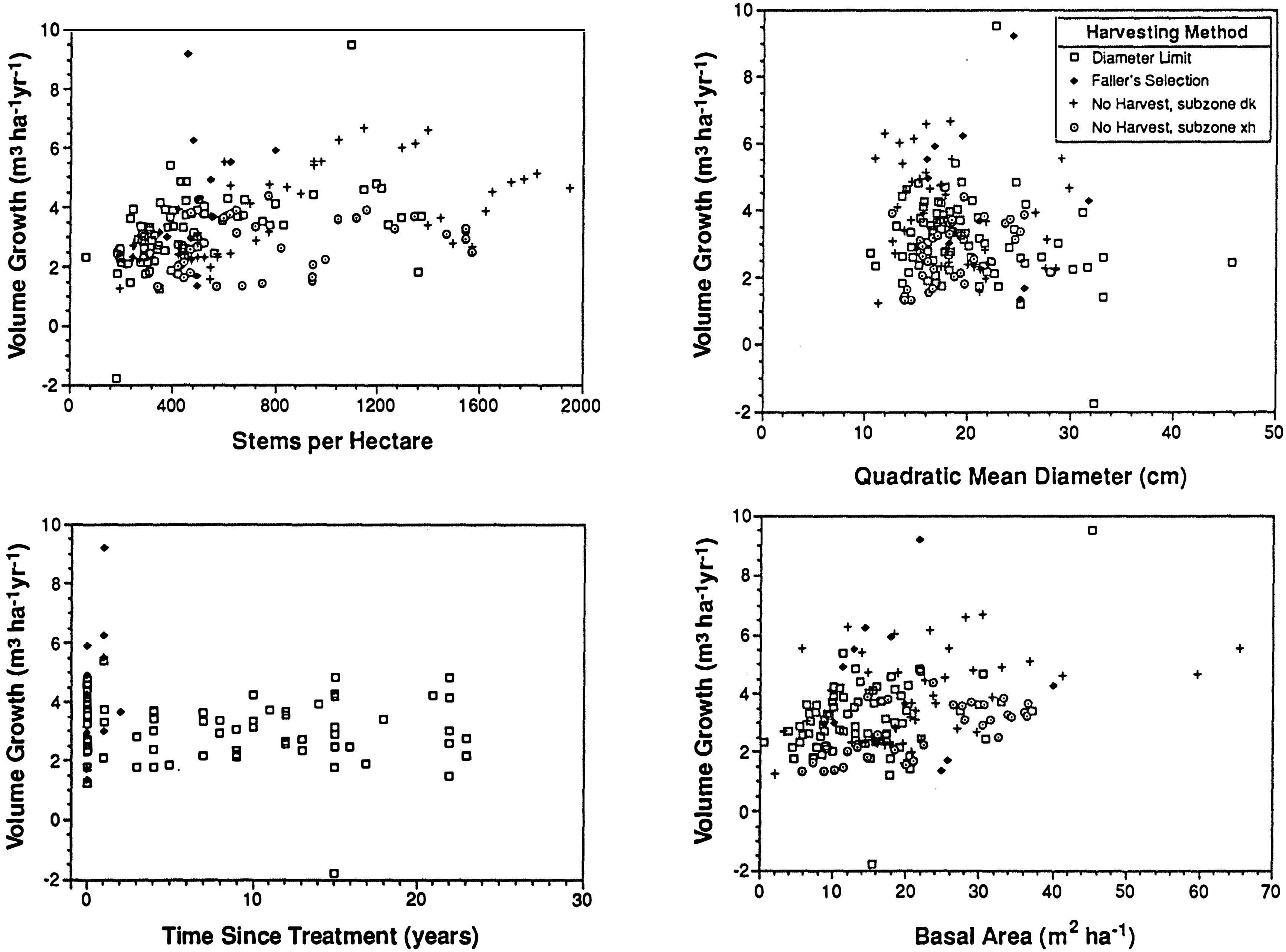
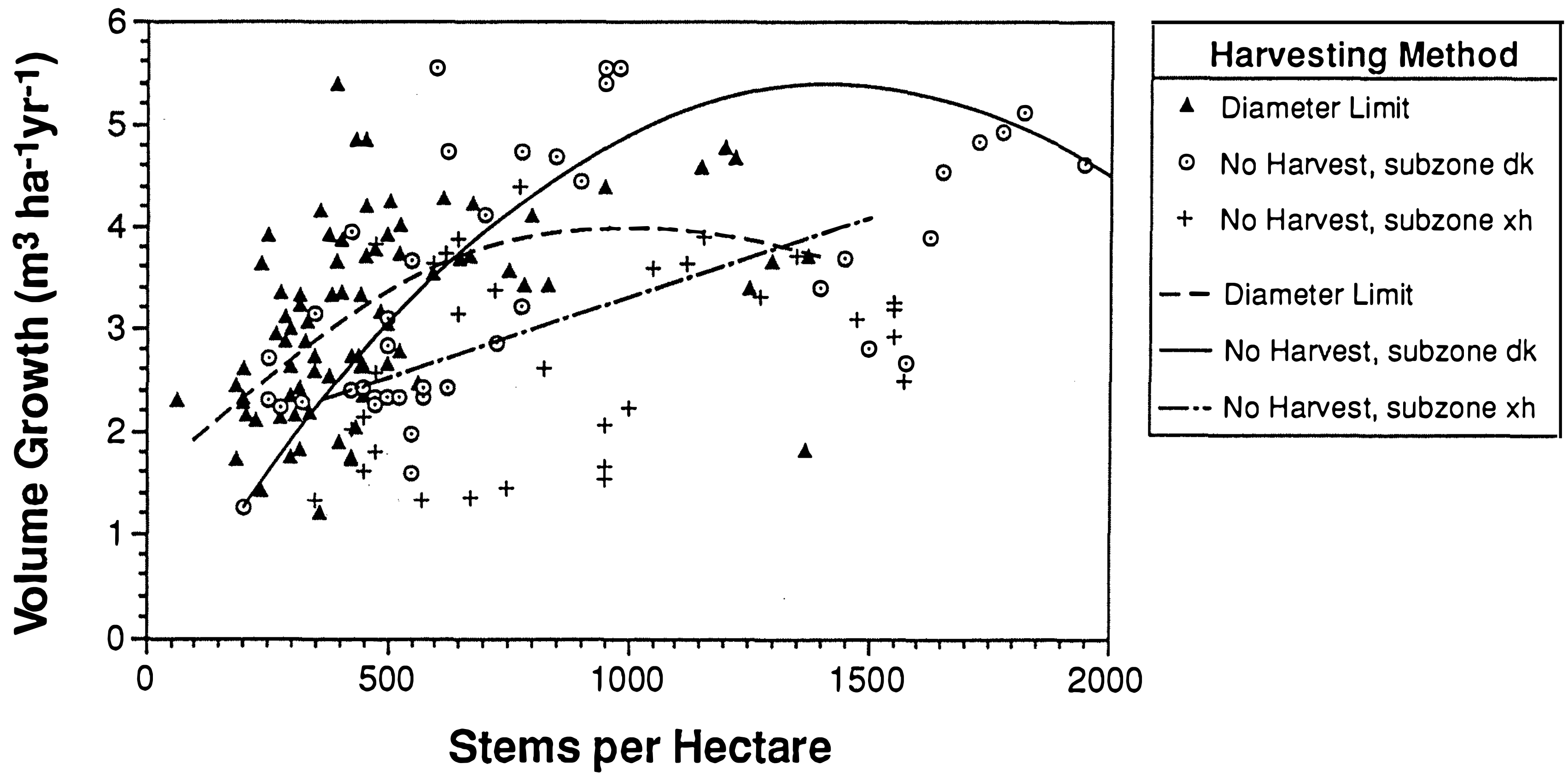


Figure 3: Growth equations resulting from the regression analyses, with individual data points, by harvesting method.



Discussion and Conclusions

The basic data set suffers from a number of deficiencies: incomplete coverage of parameter combinations and geographic locations, different measurement periods and procedures, and variability in harvesting intensity and quality. The deficiencies create considerable "noise" in the data which makes it difficult to determine relationships and trends and decreases the accuracy of the estimates.

These deficiencies in the data are compounded by a natural variability within IDF stands. For example, some uneven-aged stands include pockets of dense, small, seemingly even-aged trees. Also, the data indicate a relatively rapid increase in trees per ha with time for some plots, a result of many small trees moving into the measured size class (9.1 cm and larger).

As a result of these problems, the expected trends and differences do not appear. For example, site quality is known to have considerable influence on tree and stand growth, yet the results emerging from this study do not support that. Also, the growth rate can be expected to vary with the time since the last harvest thinning, but the data do not show that. At the same time, the trends that do appear are poorly defined, with small R^2 values and no clear choice among the variables. It is unlikely that the variables selected are the best ones, and the derived trends the true ones.

In conclusion, our knowledge of IDF growth and the factors influencing it is deficient; we need a better understanding of the basic growth processes which appears to be more complex than anticipated. Also, the data we have acquired for modelling are insufficient in terms of quantity and quality, they do not help us to develop a better understanding of the growth processes. Until both these problems have been solved, it is unlikely that good IDF growth models can be derived.

Prototyping Growth Models with the Forester's Workspace

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1. Introduction

According to the dictionary, "a prototype is an individual that contains all the essential features found in later individuals." A prototype growth simulation model should communicate the essential data and relationships found in other implementations based on the prototype. Because most existing growth models are essentially black boxes, we suggest that for all growth models there should be an "open" prototype that describes the growth process completely. It may not contain proprietary coefficients but should contain the form of all essential relationships and provide representative coefficients. We show here that use of a fourth generation prototyping language facilitates developing, evaluating, and understanding growth models. The language chosen is natural, flexible, and can be executed directly by computer.

The goal is to develop prototype models that are easily accessible in a written form, easily and precisely understood, easily adapted to new methods and data, and suitable for immediate computer analysis. The prototyping language is based on concepts from several popular programming languages. The working environment is a micro-computer including a word processor for preparation of reports, the Forester's Workspace[1] for analysis of scripts, a software package for graphical portrayal of results, and a graphical user interface (GUI) for managing the environment.

Analysis is completed using script files which consist of comments, definitions, and expression sequences to be evaluated by the computer. The programming style stresses small modular operations, appropriate problem-oriented vocabulary, and only essential data objects.

2. Growth model formulation

The general problem is: How do we model the growth of forest stands? A stand is a group of trees. A future stand is obtained by simulating growth (change) of a stand for one time period, typically one year. A growth schedule might require summaries following each of four five-year growth projections.

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[1]The Forester's Workspace operates in conjunction with Q'Nial, the IBMPC implementation of the Nial general-purpose programming language. It is available from Nial Systems Limited, 155 Queen Street, Ottawa, Ontario K1P 5C9 (613-234-4188).

Several additional questions assist in formulating a growth model. How is the growth simulation process described? After a simulator is formulated, how does it behave when applied to representative or extreme situations? A general growth simulator is presented here and applied to a typical forestry application.

2.1. Growth Simulator

A growth simulator requires five parameters that define:

1) the stand data (stand),
2) the growth method to be applied to the stand (grow),
3) the summarization to be applied to the stand (summarize),
4) the report generator for the stand summaries (report), and
5) the growth projection schedule data, a list of growth intervals or periods (schedule).

Given these parameters, the simulation should proceed as follows:

1) begin the list of results with a summary of the initial stand.
2) Get the current (first) growth period or interval (N) and delete it from the Schedule.
3) Grow the stand for N periods.
4) Append the list of results with a summary of the projected stand.
5) When all projections have been made, report the list of results.

The Forester's Workspace allows simulation of growth with these five parameters as inputs or arguments based on the following definition.

```
SIMULATE IS TRANSFORMER grow summarize report
      OPERATION Stand Schedule
      {
      Results gets solitary summarize Stand;
      WHILE not empty Schedule DO
            N Schedule gets [first, rest] Schedule;
            Stand gets N FOLD grow Stand;
            Results gets Results append summarize Stand;
      ENDWHILE;
      report Results
      }
```

Usage of simulate allows for any definition of these parameters. For example, a simple growth process can be simulated by adding 1 to a starting value of 1000. The first three parameters are operations enclosed by square brackets and separated by commas, and the last two are data enclosed in parentheses. The order is as required in the formal definition. The stand summary is ignored by simply "passing" the stand without change.

```
simulate [1+, pass,"Results table] (1000)(1 1 1 1 1 5 5 10)
Results 1000 1001 1002 1003 1004 1005 1010 1015 1025
```

A typical forestry application, the stand table growth projection, is expressed as follows:

```
simulate [stp, stpSummary, stpReport] StandP3 Stpschedule
```

where stp, stpSummary, stpReport, standP3, and stpSchedule are defined as shown below.

2.2. Stand model

For the growth models described here, a stand is a list of three items. The first two items, total age (years) and site index (average height of dominant and codominant trees at 50 years) are single values; the third item is a list of trees in the stand. Operations like "first" and "second" are predefined in the prototyping language and greatly simplify the extraction and manipulation of the items of arrays such as "stand". Definitions for species codes ("Sw), tree diameters in cm at 1.3m height (dbh), and the tree factors (trf) representing trees per hectare are made in a similar way. Box diagrams are automatically generated to show the structure of complex arrays.

```
Sw is "Sw;

standP3 gets [20, 16, [sw 5. 1500., sw 6. 2000., sw 7. 1500.]]
+--+--+-------------------------------------+
|20|16|+-----------+-----------+-----------+|
|  |  ||Sw 5. 1500.|Sw 6. 2000.|Sw 7. 1500.||
|  |  |+-----------+-----------+-----------+|
+--+--+-------------------------------------+

age         IS first;
site        IS second;
trees       IS third;
      spp   IS first;
      dbh   IS second;
      trf   IS third;

age of standP3
20

trf of third of trees of standP3
1500
```

2.3. Growth projection method

A growth projection is typically based on projecting the characteristics of a stand 1 year into the future. The Stand Table Projection (stp) method is described here since it is easily formulated and illustrates the same procedures that would be required with more complex growth relationships. Stp implements the simplest 1-year stand table projection. Future diameters (stpFdbhs) are obtained by adding annual diameter increment values (cm) to each of the three diameter classes present in the stand model, and future tree factors (stpFtrfs) are projected by reducing the trees per ha by 1 percent mortality. Separate lists of species codes (stpSpps), diameters (stpFdbhs), and tree factors (stpFtrfs) are converted to a list of trees (stpftrees) using the flip operation. Square brackets and commas delimit a list of operations to be applied to the data following the brackets.

```
stpSpps     IS each spp of trees;
stpFdbhs    IS (0.22 0.18 0.15) + each dbh of trees;
stpFtrfs    IS 0.99 * each trf of trees;
stpFtrees   IS flip [stpSpps, stpFdbhs, stpFtrfs];
stp         IS [1 + age, site, stpFtrees];
```

2.4. Stand summary

Any summarization may be made if it is derived from the data available in the stand model. This example includes a local tree volume table (stptreevol) which estimates volume of a tree based on its diameter. The stand summary (stpSummary) includes age, density per hectare, and stand volume per hectare. Results are reported (stpReport) in a simple table with column titles.

```
stpTreevol   IS OPERATION d { .00027274 * (d power 2.2501) };

stpDensity   IS sum each trf of trees;
stpAvdbh     IS div [sum each (prod [trf, dbh]) of trees, stpDensity];
stpStandvol  IS sum each (prod [trf, stpTreevol dbh}) of trees;
stpSummary   IS [age, stpdensity, stpAvdbh, stpStandvol];
stpReport    IS "Age "Density "Dbh "Vol table;
```

2.5. Growth schedule

A list of growth projection intervals. For the stand table projection they are given in years.

```
Stpschedule gets 5 5 10 10;
```

3. Growth model evaluation

Developing a prototype requires formulating the model as has been described here for a stand table projection and then evaluating its performance using stand data. A variety of growth projections are required at different times to allow 1) evaluation of individual tree characteristics, 2) evaluation of stand characteristics, 3) comparisons with other projection models or methods, and 4) comparisons among different stands.

3.1. Stand characteristics

Depending on what components are being evaluated, different summaries may be defined. Here we use the summary defined earlier for the stand table projection.

```
setdigits 1;

SIMULATE [stp, stpsummary, stpreport] standP3 Stpschedule
Age Density Dbh Vol
 20    5000.   6.   79.
 25    4755.   7.  102.
 30    4522.   8.  127.
 40    4090.  10.  184.
 50    3699.  11.  245.
```

3.2. Tree characteristics

Any defmition may be used for summaries of one or several trees in the stand. A simple example is the age of the stand and dbh of the first tree. Even though trees are the main focus here, the operation is defined for a stand, and it combines both stand and tree summary characteristics.

```
treesummary IS [age, dbh of first trees];
treereport  IS "Age "Dbh1 table;

SIMULATE [stp, treesummary, treereport] StandP3 Stpschedule
Age Dbh1
```

```
20    5
25  6.1
30  7.2
40  9.4
50 11.6
```

3.3. Growth projection methods

The Mixedwood Growth Model[2] is included here to illustrate comparison of two growth projection methods. Mgm implements an individual tree growth model using the same stand model as that presented for the stp. Definitions are displayed using the "see" operation to show that the two methods differ mainly in the way diameters and tree factors are projected into the future. In addition mgm deletes trees for which the tree factor falls below one and it allows for ingrowth of trees into the stand. Other methods are easily implemented if they use the same stand model. Age, density, average dbh, and stand volume are summarized for the two projection methods, stp and mgm.

```
fetch "mgm; setdigits 0;

each see "stp "mgm "stpFtrees "mgmFtrees
stp          IS [ 1 + age , site , stpftrees ]
mgm          IS [ 1 + age , site , mgmftrees ]
stpftrees    IS flip [ stpspps , stpfdbhs , stpftrfs ]
mgmftrees    IS SELECTBY (1<trf) link [flip[spps,fdiams,ftrfs], ingrowth]

mgmsummary   IS [age, tpha, dbha, vol];
mgmreport    IS "Age "Density "AvDbh "Volume table;

(SIMULATE [stp, stpSummary, stpReport] StandP3 Stpschedule)
(SIMULATE [mgm, mgmSummary, mgmReport] StandP3 Stpschedule)
+--------------------+--------------------+
|Age Density Dbh Vol |Age Density Dbh Vol |
| 20   5000.  6.  79.| 20   5000.  6.  45.|
| 25   4755.  7. 102.| 25   4826.  8.  93.|
| 30   4522.  8. 127.| 30   4609. 10. 135.|
| 40   4090. 10. 184.| 40   4090. 12. 196.|
| 50   3699. 11. 245.| 50   3548. 13. 234.|
+--------------------+--------------------+
```

This comparison between the stp and mgm projections shows some interesting differences which may require further investigation. Initial conditions are identical except for total volume per hectare; there is a major difference in the volume estimation methods between these two models. Densities for mgm are greater than for stp until age 50 when the stp shows greater density. Average diameter is consistently greater with the mgm projections and this leads to larger stand volumes at ages 30 and 40 years since the densities are similar at those ages.

Using "copy-and-paste" operations, tabular results of a growth projection are easily transferred from the Forester's Workspace to a spreadsheet/charting program for graphic illustration.

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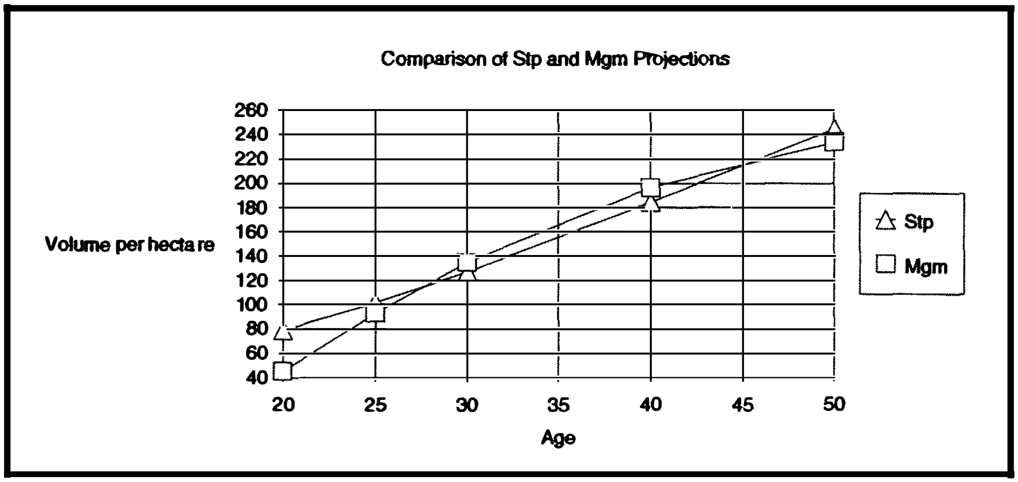
[2] Morton and Titus 1984 and 1990, internal reports to Research Branch, Alberta Forest Service.



3.4. Stands

Often several stands with different characteristics are to be compared using the same stand summary. Eachleft is a transformer that allows several stands (standlist) to be grown with the same simulation parameters. StandP4 is the same as StandP3 except that the density is doubled for each tree.

```
StandP4 gets [20, 16, [sw 5 3000., sw 6 4000., sw 7 3000.]];

StandP3 StandP4 eachleft SIMULATE [mgm,mgmsummary,mgmreport] Stpschedule
+--------------------+--------------------+
|Age Density Dbh Vol |Age Density Dbh Vol |
| 20    5000.  6.  45.| 20   10000.  6.  90.|
| 25    4826.  8.  93.| 25    9397.  7. 136.|
| 30    4609. 10. 135.| 30    8673.  8. 168.|
| 40    4090. 12. 196.| 40    7154.  9. 208.|
| 50    3548. 13. 234.| 50    5829. 11. 230.|
+--------------------+--------------------+
```

Several interpretations are made from this result: 1) relative mortality is greater in the less dense stand (3548/5000 = .7); 2) trees in the more dense stand have a smaller average diameter; 3) while total volume in the more dense stand is greater initially, by 50 years the less dense stand shows slightly greater volume.

3.5. Schedules

Both regular and irregular growth periods may be used interchangeably by providing the schedule as a list of growth periods. The following specification schedules five five-year, five ten-year, and five twenty-year summaries over a 175 year projection. For a simple stand table projection 175 years is too long, but it could be used with mgm .

```
mgmSchedule gets 5 5 5 5 5 10 10 10 10 10 20 20 20 20 20;
```

STAND DENSITY MANAGEMENT DIAGRAMS AND THEIR DEVELOPMENT AND UTILITY IN BLACK SPRUCE (Picea mariana (Mill.) B.S.P.) MANAGEMENT[1]

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SUMMARY

Stand density management diagrams are average stand-level models which graphically illustrate the relationships between yield, density and mortality at various stages of stand development. These diagrams are used to derive density control regimes by stand management objective. Although developed for some of the commercially important species within the Pacific Rim region, diagrams have yet to be developed for the intensely managed boreal species. The objectives of this study were to (i) develop stand density management diagrams for black spruce (Picea mariana (Mill.) B.S.P.), and (ii) given (i), demonstrate their potential utility in density management. However, before these objectives were realized, the underlying concepts and historical development of stand density management diagrams were reviewed.

Stand density management diagrams were initially developed by Japanese scientists in the early 1960's. The reciprocal equations of the competition-density (C-D) and yield-density (Y-D) effect, -3/2 power law for self-thinning, beginning curves of competition (crown closure) and natural thinning (density-dependent mortality), and isolines representing equivalence in competition (relative density index) and size (mean diameter), were the principal relationships employed. During the 1970's, modifications consisting of replacing the reciprocal equations with empirically-based volume-density relationships, using different relative density indices and incorporating forest production theories, were proposed. Alternative reformulations for the diagrams were derived in the 1980's, ranging from using different size variates (replacing mean volume with diameter) to calibrating diagrams based on a system of temporal-dependent equations.

Stand density management diagrams for black spruce were developed using data derived from 49 0.081-ha semi-permanent sample plots and 257 open-grown sample trees, located in natural stands throughout central insular Newfoundland. The resultant diagrams illustrated the reciprocal equation of the C-D effect, -3/2 power law for self-thinning, approximate crown closure line, zone of imminent competition-mortality (density-dependent mortality), and relative density index, diameter and merchantable volume/total volume ratio isolines. Potential application of the diagrams for evaluating commercial thinning alternatives were demonstrated. Limitations of the diagrams and future research directions were identified.

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[1] Manuscript in preparation.

FORCYTE-11 and intensive management of Douglas-fir: Examination of some of the model's short- and long-term predictions of biomass production.

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ABSTRACT

Concern over the long-term productivity of forests with intensive biomass harvest has led to the development of FORCYTE-11, an ecosystem-based model which can be used to examine the impacts of different management schemes. Although calibrated and used to examine management impacts for several of forest types, the model has not been tested against an independant data set. FORCYTE-11 predictions were compared to 15 years of data from a thinning and fertilization experiment in a low site quality, 40-year-old stand of Pseudotsuga menziesii at Shawnigan Lake, B.C. (east coast of Vancouver Island). Data for 23 variables were compared but only data on stand biomass and density are reported in this paper. Initial comparisons with the uncalibrated model showed that model simulations were reasonable, with growth in treated plots tending to be more accurately predicted than in control plots. This was probably due to the model's weakness in its simulation of decomposition and soil organic matter. After calibration with control plot data and inclusion of an understory species, Gaultheria shallon, model fit improved, but its accuracy showed strong biases which varied with the thinning and fertilization treatments. The model was able to correctly predict the rankings of all 15 treatments. Using the control plot dataset for Shawnigan Lake, FORCYTE-11 was then used to examine the effects of intensive forest management on long-term productivity. The model predicted that yield would decline the most over time with short-rotation, whole-tree harvest. Effects of initial site conditions caused high biomass yields in either the first or second rotation, depending upon rotation length. Iterative simulations with the model suggested that to keep yield constant with successive rotations, large fertilizer additions were needed, especially with short-rotations. The model proved quite sensitive to variation in N inputs through precipitation, cumulative 360-year yields declined by 18% when N inputs were reduced from 2.0 to 0.5 kg N $(ha\ yr)^{-1}$.

INTRODUCTION

Increasing concern over the sustainability of forestry has increased the need for knowlege on the long-term impacts of forest practices. Unfortunately data from long-term experiments are not available to answer many of the questions raised (Kimmins 1985). In the absence of adequate data, computer models of forests have been developed to examine the effects of forestry on long-term productivity. FORCYTE-11, an ecosystem-based, forest management simulator, is one such model (Kimmins et al. 1990). The model was developed over the last decade and although widely used has not been tested against a dataset of independent empirical results. While data from experiments of several rotations in length would be ideal in testing the model, such data are not available for Douglas-fir. In absence of long-term data, data from shorter-term empirical trials can be used to see if the model's behaviour is reasonable, prior to using the model to examine the potential effects of intensive forest management.

The objectives of this study were two-fold. The first, was to briefly report on results of the calibration and testing of the short-term predictions of FORCYTE-11, against 15 years of data from experiments in Douglas-fir at Forestry Canada's Shawnigan Lake Research Site. The second, was to examine some of the predictions of FORCYTE-11 as to the long-term effects of intensive forest management on biomass production.

TESTING FORCYTE-11'S SHORT-TERM PREDICTIONS

Experimental site and data

FORCYTE-11 was calibrated and tested using data from the Shawnigan Lake experiment. The experiment was started in 1970 in a 24 year-old stand of *Pseudotsuga menziesii* near Shawnigan Lake, British Columbia (123°43'W 48°38'N). The site is transitional between the very dry maritime Coastal Western Hemlock and wet Coastal Douglas-fir biogeoclimatic subzones and has a site index of 21m in 50 yrs (total age). Soils developed from coarse-textured till, have thin organic layers (<2 cm) and are classified as Orthic Dystric Brunisols (Dystrochrept Inceptisol, U.S.) (Crown and Brett 1975). Ten years prior to planting, the site burned, was salvage logged, burned again and was then planted with 2-0 stock in 1948 (Crown and Brett 1975). In 1970 the site contained 4,695 stems ha^{-1} with a basal area of 25 m^2 ha^{-1}. The main experiment is a 3 x 3 factorial design established in 1971 with 4 plots per treatment and 3 levels of thinning; (T0 - control, T1 - 1/3 basal removed, T2 - 2/3 basal area removed) and 3 of fertilization (F0 - control, F1 - 224 kg urea N ha^{-1}, F2 - 448 kg urea N ha^{-1}). In 1981 half of the fertilized plots were refertilized (F1-1, F2-2) giving a total of 15 treatments.

After the creation of an initial ECOSTATE file (Kimmins et al. 1990) that approximated stand history prior to 1948, runs of FORCYTE-11 were made, using the PROBE multiple-run simulation software (Apps et al. 1988), to simulate the four thinning and fertilization treatments, T0F0, T0F2, T2F0, and T2F2. Data for 23 variables were available (Godfrey et al. 1988). Available data included: 6 stand-level biomass variables, 3 individual tree biomass variables, 6 stem density and mortality variables (Gardner 1990), 4 height variables (Gardner 1990), litterfall (Trofymow et al. in press), net assimilation rate (Brix 1983), foliar N (Pang et al. 1987) and foliar increment (Brix 1983). Depending upon the variable, data were available for a 15-year period, stand ages 24-39 years, on a yearly or three-year basis. Biomass data were from a biomass sampling at 9-years (Barclay (et al. 1986), with data for intermediate years calculated using stand table information (Gardner 1990) and biomass regression equations (Barclay et al. 1986). Only comparisons of stemwood biomass, stem density and foliar biomass are presented in this paper. A more exhaustive comparison of all 23 variables is available in a separate report (Sachs and Trofymow in press).

Initial testing and calibration

The model was tested in two phases: In Phase I the model was run uncalibrated for the site using data sets provided by the model's authors but initialized so that stocking, stand conditions, and treatments were identical to those at the start of the experiment. Stand growth was simulated to 60 years. In Phase II, the model was calibrated for site and stand growth conditions in control plots from 24-39 years, and an understory plant, salal, (*Gaultheria shallon*) was included in the simulation. The model was then rerun for the four treatments.

Initial comparisons of data with the uncalibrated model showed that the model simulated stemwood production more accurately in thinned plots than in unthinned plots (Fig. 1). This difference in accuracy was also reflected in the model's simulation of stem density in unthinned treatment, which declined at a greater rate than predicted, especially with fertilization (Fig. 2). Large amounts of available N early in stand development caused foliar biomass in all treatments to increase too rapidly, resulting in initially large overestimates of foliage in treated plots and a decrease in foliage in control plots (Fig. 3). Poor results for control plots particularily foliar biomass were probably due to the model's weakness in its simulation of decomposition and soil organic matter as it predicted humus levels of about 20 Mg ha^{-1} while actual levels were greater than 100 Mg ha^{-1} (Sachs and Trofymow in press). After calibration with control plot data and inclusion of salal to reduce the initial rapid foliage increase, simulations of stemwood biomass showed marginal changes (Fig. 1), stem density improved in control but worsened in TOF2 treatments (Fig. 2), and foliar biomass improved in all treatments (Fig. 3).

Comparisons with all treatments
Simulations were then conducted for all 15 treatments, and model predictions were compared to data for stemwood volume (m^3 ha^{-1}) and stem density (number ha^{-1})(Gardner 1990). FORCYTE-11's predictions of stemwood biomass were converted to volume using a constant wood-density of 0.42 g cm^{-3}.

The changes in accuracy of the model's predictions with thinning and fertilization became clear when comparisons were made across the range of treatments. The model went from consistently underestimating stemwood volume in unthinned treatments to overestimating volumes in heavily thinned treatments (Change in Mean diff. and significant runs tests, Table 1). At intermediate thinning levels the model was less biased. In addition, the level of bias changed with the rate of fertilization. For unthinned treatments, bias decreased as fertilization rates increased while with heavy thinning bias increased as rates increased. Generally, the type of bias depended on the degree the model over or underestimated the data. The larger the mean difference between model and data, the more likely bias was variable (difference in slope) instead of constant (difference in offset).

As expected, model predictions of stem density were most accurate in heavily thinned treatments, less accurate at intermediate thinning and least accurate in unthinned treatment (Mean diff. and runs, Table 1). As the model had been initiated with the actual stem density in each treatment it would remain identical to the treatment as long as little mortality occurred. The model's predictions of stem density generally worsened with increasing fertilization. Since it was not able to accurately predict the increase in fertilizer induced mortality the difference between the model and data increased through time resulting in a large variable bias (relative difference between Fne*, Fce* and Fne*, Table 1).

Although the model had problems in accurately predicting the actual values for some of the treatments, its rankings of stemwood volume and stem density each year for the different treatments were not significantly different from that observed (Sachs and Trofymow in press). For example, for model predictions and data at year 15 (Table 1), Spearman's rank correlation coefficients (Snedecor and Cochran 1976) were 0.818 for stemwood biomass and 0.971 for stem density (significant if <0.514 - 5% level or <0.614 - 1% level).

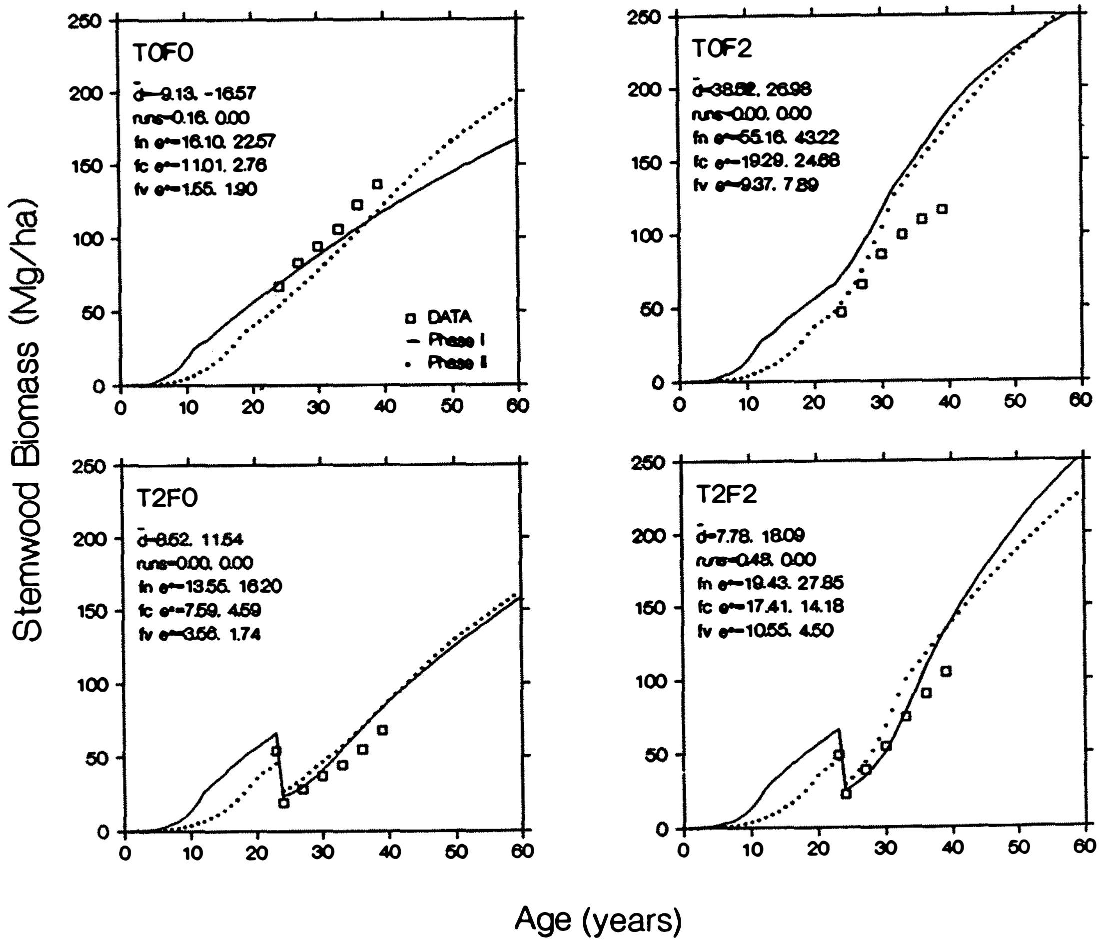

Fig. 1. Predicted and measured stemwood biomass under four thinning and fertilization treatments at Shawnigan Lake. Statistics indicate the mean difference (d), runs test p value (runs), Freese e values uncorrected (fne*) and corrected for constant (fce*) or variable bias (fve*). Results for Phase I are the first of each pair of numbers, Phase II the second of the pair. See Table 1 for further explanation of each statistic.

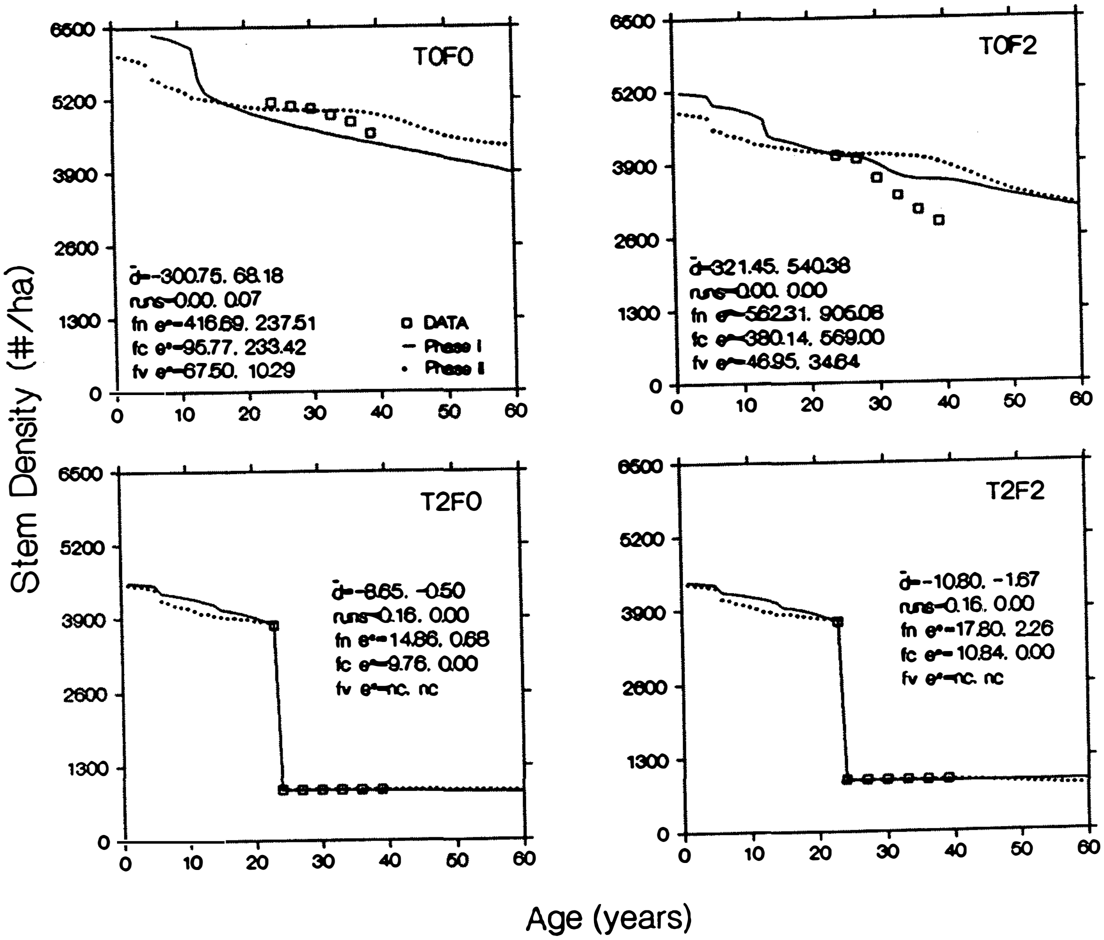

Fig. 2. Predicted and measured foliage biomass under four thinning and fertilization treatments at Shawnigan Lake. Statistics indicate the Mean difference (d), runs test p value (runs), Freese e values uncorrected (fne*) and corrected for constant (fce*) or variable bias (fve*). Results for Phase I are the first of each pair of numbers, Phase II the second of the pair. See Table 1 for further explanation of each statistic.

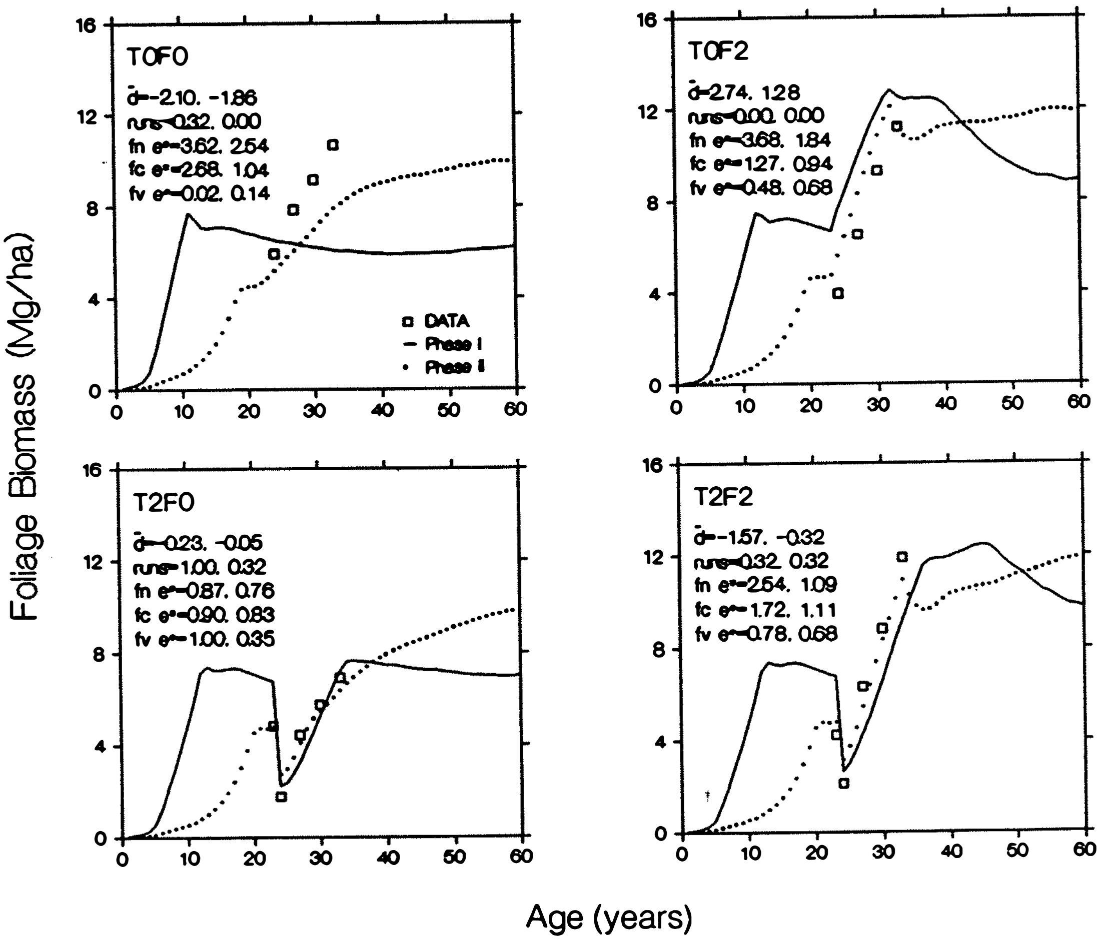

Fig. 3. Predicted and measured number of tree per hectare under four thinning and fertilization treatments at Shawnigan Lake. Statistics indicate the mean difference (d), runs test p value (runs), Freese e values uncorrected (fne*) and corrected for constant (fce*) or variable bias (fve*). Results for Phase I are the first of each pair of numbers, Phase II the second of the pair. See Table 1 for further explanation of each statistic.

Table 1. Comparisons of FORCYTE-11 model predictions and data for 15 treatments at Shawnigan Lake for stemwood volume (m3/ha) and stem density (number/ha). Statistics indicate 15-year post-treatment (stand age 39 yrs) values for the model and data; mean difference (Mean Diff.) between model and data over all years; runs test probability values[a] (Runs); Freese e values[b] for no bias (Fne*), or corrected for constant bias (Fce*) or variable bias (Fve*).

Treatment	15 Year Model	15 Year Data	Mean Diff.	Runs	Fne*	Fce*	Fve*
		Stemwood Volume (m^3/ha)					
T0F0	278	356	-57.65	0.00	86.11	38.91	3.16
T0F1	331	387	-26.28	0.00	43.89	27.45	6.73
T0F1-1	393	442	-52.69	0.00	74.75	23.98	7.56
T0F2	400	414	26.33	0.00	37.34	11.93	11.94
T0F2-2	497	456	12.97	0.48	30.97	27.21	17.08
T1F0	243	294	-20.76	0.08	43.08	34.79	2.34
T1F1	299	346	-2.76	0.08	29.30	31.00	12.37
T1F1-1	362	390	-17.38	0.16	31.49	22.34	4.30
T1F2	366	394	9.17	0.16	23.02	20.68	17.17
T1F2-2	475	458	-21.18	0.16	32.76	16.93	16.76
T2F0	222	221	28.09	0.00	40.70	15.55	4.28
T2F1	288	286	30.40	0.16	48.29	26.99	15.34
T2F1-1	348	320	44.96	0.00	61.36	8.77	9.23
T2F2	354	339	48.49	0.00	67.19	15.50	16.74
T2F2-2	453	348	69.60	0.00	100.03	35.99	9.45
		Stem Density (number/ha)					
T0F0	4791	4283	203.17	0.00	360.78	249.22	6.08
T0F1	3511	2979	206.13	0.00	383.81	281.21	11.16
T0F1-1	3616	2522	506.46	0.16	863.81	560.93	10.27
T0F2	3898	2855	519.53	0.00	882.65	569.35	34.46
T0F2-2	3045	2262	353.33	0.16	620.46	421.83	37.55
T1F0	1966	1922	19.33	0.16	32.26	20.13	2.37
T1F1	1809	1718	23.85	0.48	54.08	46.25	3.48
T1F1-1	1876	1805	13.81	0.08	42.26	40.42	3.01
T1F2	1984	1916	37.33	0.08	77.99	63.38	10.98
T1F2-2	1982	1768	82.38	0.48	153.54	112.61	15.63
T2F0	894	898	-1.55	0.00	2.10	0.00	nc
T2F1	935	915	2.75	0.48	11.12	11.18	2.65
T2F1-1	885	865	10.85	0.16	16.78	8.65	1.56
T2F2	908	915	-2.43	0.16	4.71	3.60	nc
T2F2-2	850	853	6.83	0.16	13.13	9.94	10.64

[a] A runs test $p < .08$ indicates that a significant serial pattern in the differences exists resulting from consistent under or overestimates by the model (Snedecor and Cochran 1976).

[b] Freese e values (Freese 1960) can be interpreted as the absolute error that can be tolerated to accept the accuracy of the model at alpha=0.08. The model was judged biased if Fce* was less than 1/5 Fne* (constant bias), or Fve* was less than 1/5 Fce* (variable bias).

FORCYTE-11'S LONG-TERM PREDICTIONS

Using the initial state file developed for the Shawnigan Lake calibration and testing we then used the model to examine the effects of intensive forest management on long-term productivity, test if fertilization could amelioriate those effects and test the sensitivity of the model to differences in N inputs through precipitation.

Prior to running the long-term simulations experiments, precipitation inputs of N in the SOILDATA file were changed. The author's initial data set for the model (Kimmins et al. 1990) indicated N inputs of 5.0 kg N $(ha\ yr)^{-1}$ from precipitation and, depending upon site quality, 1.0-3.0 kg N $(ha\ yr)^{-1}$ from non-symbiotic N-fixation. Although precipitation inputs were unchanged with model calibration, it was found necessary to keep N-fixation inputs constant at 0.5 kg N $(ha\ yr)^{-1}$ in order to overcome a positive feedback in the model (Sachs and Trofymow in press). While precipitation inputs of 5.0 kg N $(ha\ yr)^{-1}$ are not unusual especially next to or downwind from highly populated areas (Schulze et al. 1989), they are high for Douglas-fir forests in the Pacific northwest. In four Douglas-fir stands in coastal Washington and Oregon, rates of input ranged from 0.9-2.0 kg N $(ha\ yr)^{-1}$ (Kimmins et al. 1985). Based on these data, precipitation inputs were changed to 2.0 kg N $(ha\ yr)^{-1}$ for the long-term simulations. Inputs from non-symbiotic N-fixation remained unchanged at 0.5 kg N $(ha\ yr)^{-1}$.

Salal removal and rotation length

We first compared the effects of rotation length (30, 60, 90, and 120 years) and salal removal on yield over a 360 year period. A conventional, stems-only (85% of stems and bark), harvest was simulated each rotation. Previous gaming with FORYCTE-11 (Sachs et al. 1989) and its predecessor, FORCYTE-10, (Kimmins and Scoullar 1984, Kellomaki and Seppala 1987) has demonstrated that rotation length can affect long-term site productivity, short rotations causing yield to decline each rotation. Yield may decline for several reasons. Nutrient loss is thought to be greater during the first years after harvest, prior to stand establishment, because of increased nutrient mineralization and leaching or erosion. Thus, the shorter the rotation, the greater the amount of time the site is without tree cover, and the greater the nutrient loss. Additionally, with short-rotations more nutrients may also be exported from the site through biomass removal since a greater proportion of the biomass removed from younger forests is juvenile wood which has a higher N concentration than older mature wood (Pang et al 1987). Thus, over the long-term more juvenile wood and nutrients would be exported from sites with short-rotation than long-rotation forestry.

In our simulations we expected that the shorter the rotation length the greater the decrease in yield each rotation. Additionally, because salal was simulated to have its greatest effects early in stand development (Fig. 3) and to be shaded out after crown closure (Sachs and Trofymow in press), we expected that salal removal would have its greatest effect on short-rotation yields and be of less importance with longer rotations.

While the shortest rotation showed long-term declines in predicted yield and longer rotations did not, increases in yield from the first to second 30 year rotation and high yields in the first of the 60, 90 and 120 year rotations were also predicted (Fig. 4). These increases were likely due to the initial starting state. The site had burned twice prior to planting and as a result all of the low C:N litter, which would have initially mineralized N, was lost. During the first 25 years, N availability would be low as logs left from the fires were decomposing but not mineralizing N and N was slowly accumulating from precipitation and N-fixation, thus yields for the first 30 yrs were low. After 30-60 years as logs became humus and mineralized N, N availability was greater and so yields in the second 30-year rotation and the first of the 60, 90 and 120 year rotations were higher. As the pulse of N mineralized from the logs diminished, yield became dependant upon the balance of N inputs from precipitation and fixation and losses through harvest. This illustrates the importance of the initial starting state and the role litter and woody debris, accumulated in the past, plays in the productivity of current and future forests.

Removal of salal had minor effects, slightly increasing predicted yield at each rotation (Fig. 4). No matter what the rotation length, cumulative yields were highest with salal removed (Table 2). Although not dramatic, the highest yield increase with salal removal occurred in the shortest rotation (117%) and lowest in the longest rotation (107%). Cumulative yields for the 60-year rotation were the highest of all rotation ages, marginally greater than the 30-year rotation (Table 2).

<u>Rotation length, harvest type and fertilization</u>

We next examined the interaction of rotation length (30 or 90 years), harvest type (stems-only, 85% stems and bark; whole-tree, 88% stems and bark, 90% branches) and N fertilization (none, constant rate, variable rate) on long-term yield. Whole-tree harvest has been demonstrated in model simulations (Kimmins and Scoullar 1984, Kellomaki and Seppala 1987, Sachs et al. 1989, Borman and Gordon 1989) and in some short-term field trials to reduce site productivity (review of Morris 1989). The primary cause is loss of nutrients from the site through increased removal of biomass, especially foliage, with higher nutrient concentrations. Thus, we expected that declines in yield would be greatest with short-rotation whole-tree harvest and least with long-rotation stems-only harvest.

Since intensive forestry was expected to cause yield to decline we tried to find the amount of fertilizer that would be needed to offset the decline. Two fertilization regimes were used; 1) the amount of N added each rotation was constant, 2) the amount of N added each rotation varied. In both regimes, N was added once each rotation at year 15. The purpose of the constant addition was to find, through repeated interations for each harvest and rotation type, the amount of N fertilizer that had to added over the entire 360 years so that the yield at the last rotation was equal to that at the first rotation. The purpose of the variable addition was to find the amount of N needed each rotation to keep biomass yield constant.

As expected, the decline in predicted yield per rotation was greatest with 30-year, whole-tree short-rotation harvest (20-30% decrease, 2nd to last rotation) and least in 90-year stems-only harvest (8-12% decrease, 1st to last rotation) (Fig. 5). The effects of initial site conditions on first and second rotation yield were seen in both harvest types, 30-year yields initially increasing before dropping, 90-year yields dropping then remaining relatively constant.

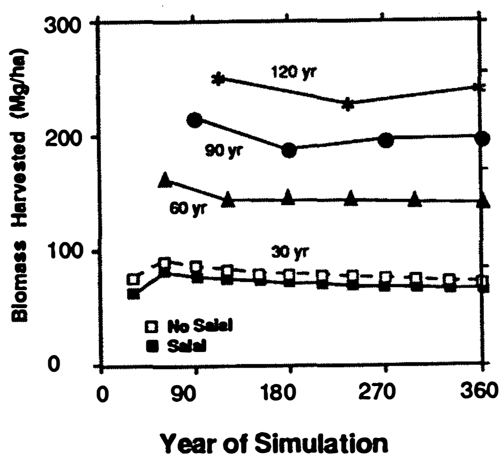

Fig. 4. Predicted effects of rotation length and salal removal on biomass harvested each rotation for Douglas-fir at Shawnigan Lake. For clarity, the effects of salal removal are only shown for the 30-year rotation, 60, 90 and 120 year rotations were similar.

Table 2. Simulated effects of rotation length and understory removal on cumulative stemwood yields (Mg/ha) over 360 years.

	Rotation length (years)			
Management	30	60	90	120
Salal present	852	889	795	709
Salal removed	962	965	854	756

With constant fertilization it was impossible to raise yields in the first 30-year rotation to match the last rotation, inputs of 80 and 150 kg N(ha rotation)$^{-1}$ kept yields constant and equalled those in the 2nd rotation (Fig. 5). Additions of 70-80 kg N(ha rotation)$^{-1}$ for 90-year rotations, caused yields to recover to those in the first rotation. For constant yield, large N inputs (500-600 kg N(ha)$^{-1}$) were needed to increase yield for the first 30-year rotation, but after some variation, the amount of N needed each rotation declined to a relatively steady level of 98 kg N(ha rotation)$^{-1}$ for stems-only harvest and 185 kg N(ha rotation)$^{-1}$ for whole-tree harvest. Because of high yields the first rotation, the 90-year scenarios were not fertilized until the second rotation after which N requirements declined each successive rotation.

Within each fertilization regime, the greatest cumulative yields over 360 years came with the 30-year whole-tree harvest and least in the 90-year stems-only harvest (Table 3). From 6-10 times as much N was needed to keep yields constant in the 30-year versus 90-year rotations, although it did cause cumulative yields in the 30-year rotations to increase by 55-88%. The variable fertilization regime was more efficient (incremental biomass yield with fertilizer/ amount of N added) at increasing cumulative yield than the constant regime in the 90-year rotations (0.30 vs 0.25, Mg wood/kg N) but was marginally less efficient in the 30-year rotations (0.29 vs 0.31 Mg wood/kg N). This was due to the need for N to raise the yield of the first 30-year rotation, while no N was needed for the first 90-year rotation.

<u>Sensitivity to N inputs from precipitation</u>

Since tree growth and yield in the model and at Shawnigan Lake were sensitive to N fertilization, we decided to examine some of the assumptions made regarding annual N inputs from precipitation. Even a rate of 2.0 kg N (ha yr)$^{-1}$ maybe too high for Shawnigan Lake, which is removed from mainland sources of N. For example, rates of N input from 1980-89 for Olympic National Park - Hoh River, almost due south of Vancouver Island, ranged from 0.34 - 1.2 kg N (ha yr)$^{-1}$ with a 10-year mean of 0.92 kg N (ha yr)$^{-1}$ (National Atmospheric Deposition Program 1989). Thus, to test the sensitivity of the model to rate of N input, we reran the rotation and harvest simulation but with three different rates of N input through precipitation 0.5, 1.0 and 2.0 kg N (ha yr)$^{-1}$. Inputs of N from fixation remained at 0.5 kg N (ha yr)$^{-1}$. We expected that the lower the rate of N input the more drastic the yield reduction over time.

As hypothesized, the model proved sensitive to variation in N inputs. Reducing N inputs to 0.5 kg N (ha yr)$^{-1}$ caused yield to drop by 35-45% from the 2nd to last 30-year rotation and by 25-30% from the first to last 90-yr rotation as compared to 20-30% (30-year) and 8-12% (90-year) reductions at 2.0 kg/N (ha yr)$^{-1}$ (Fig. 6). Reductions were greatest with whole-tree harvest. Cumulative 360 year yields at 0.5 kg N (ha yr)$^{-1}$ were 17-18% lower than those at 2.0 kg N (ha yr)$^{-1}$, irrespective of harvest type and rotation age (Table 4).

CONCLUSIONS

FORCYTE-11 did suprisingly well in predicting the short-term effects of stand management on growth and yield considering that the calibration data used were for a short period and for a limited range of sites. Further calibration data for higher quality sites for a longer period of time would probably increase the accuracy of the model predictions, especially changes in stem density, and

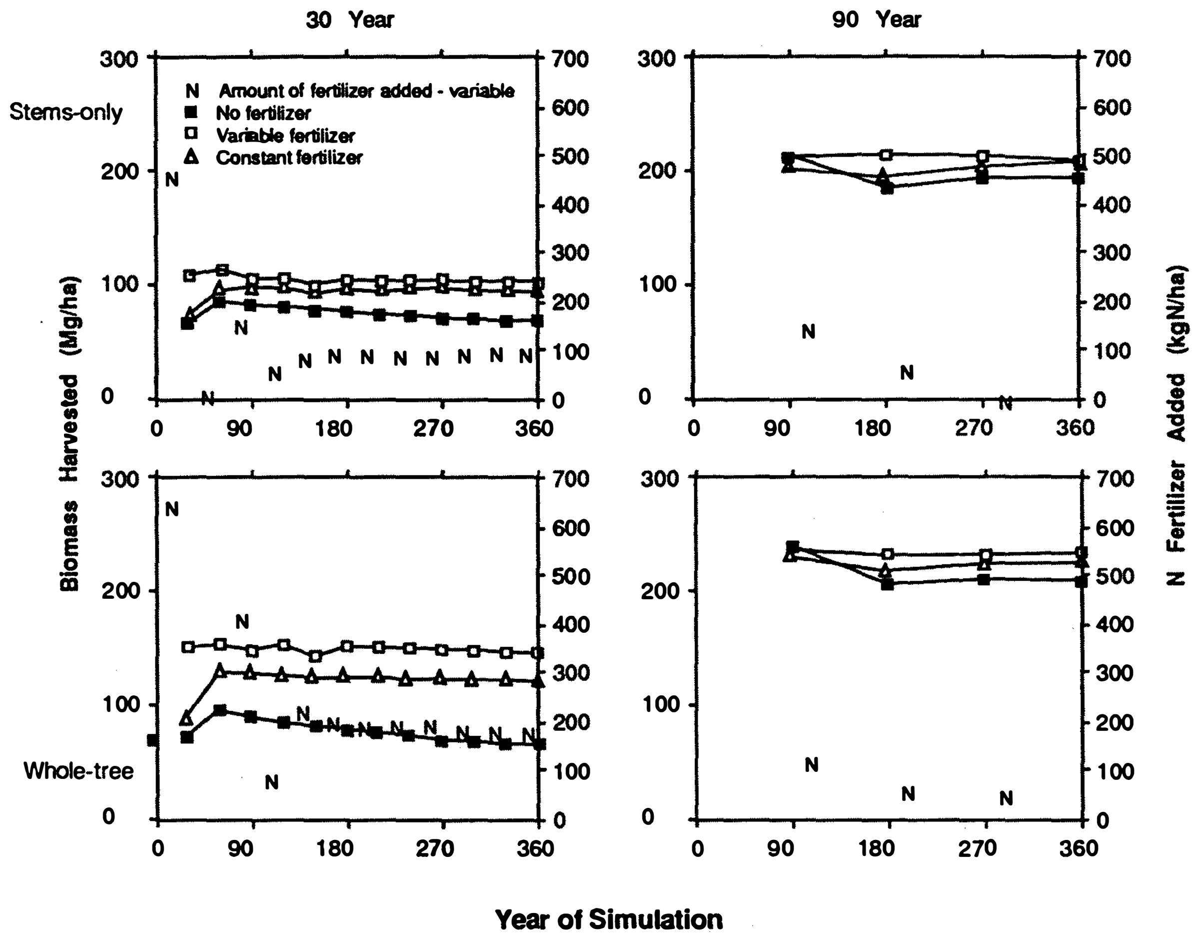

Fig. 5. Potential effects of rotation length, harvest type and fertilization on biomass production each rotation for Douglas-fir at Shawnigan Lake. All simulated N additions occurred once each rotation, at stand-age 15-years, starting with the first 30-year rotation and the second 90-year rotation. Amounts of N added with variable fertilization are shown on the figure. Constant fertilization N additions were: 80 kg N/ha, 30-year stems-only; 150 kg N/ha, 30-year whole-tree; 70 kg N/ha, 90-year stems-only; 80 kg N/ha 90-year whole-tree.

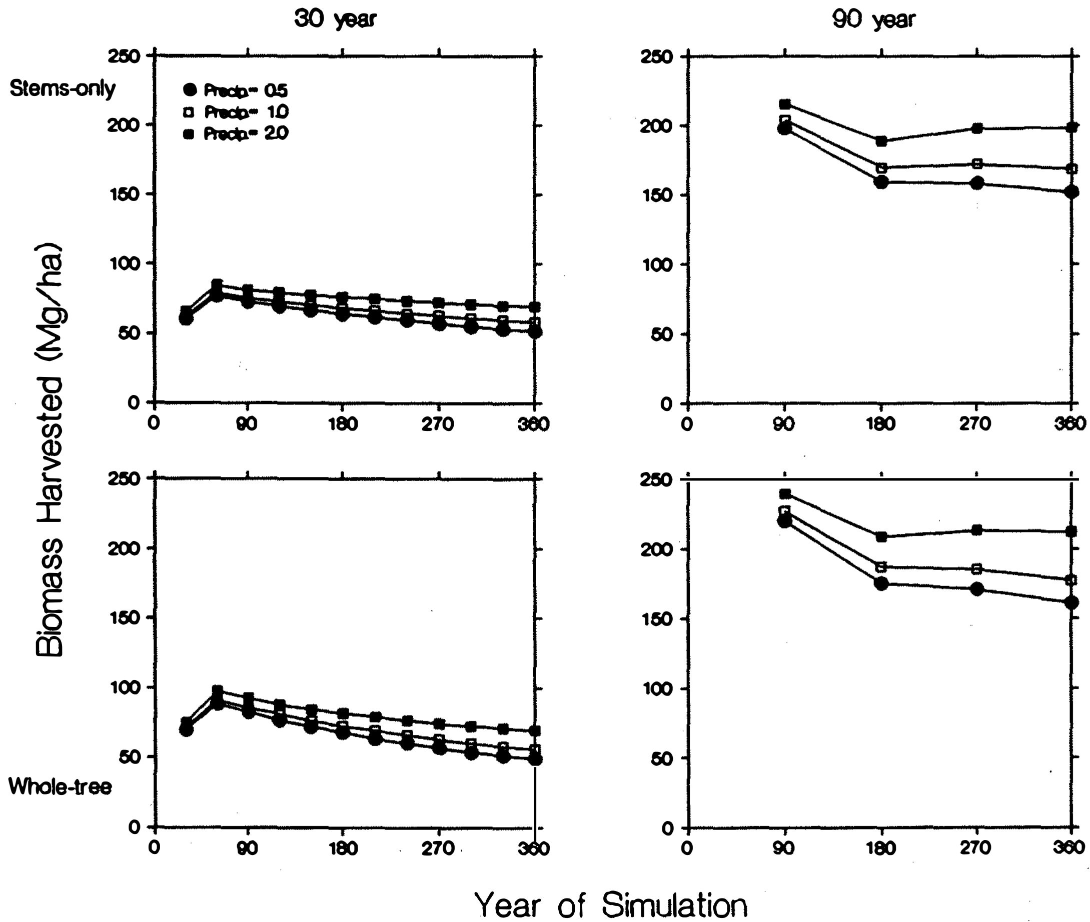

Fig. 6. Predicted effects of rotation length and harvest type on biomass production each rotation for Douglas-fir at Shawnigan Lake assuming different N inputs from precipitation (kg N (ha yr)$^{-1}$). Non-symbiotic N inputs were assumed to remain constant at 0.5 kg N (ha yr)$^{-1}$.

Table 3. Potential effects of rotation length, harvest type and fertilization, on cumulative wood yields (Mg/ha) over 360 years. Values in brackets indicate the total amount of N fertilizer (kg/ha) added in that treatment over the entire 360 years. Constant rate applications had equal amounts of N added each rotation, variable rate applications had N added to maintain yield at each rotation constant.

	30 yr rotation		90 yr rotation	
Fertilization regime	stems only	whole tree	stems only	whole tree
No fertilizer	893 (0)	962 (0)	800 (0)	873 (0)
Constant rate	1178 (960)	1544 (1800)	852 (210)	936 (240)
Variable rate	1260 (1340)	1789 (2650)	863 (207)	951 (265)

Table 4. Model sensitivity to levels of annual N input (kg N (ha $yr)^{-1}$) through precipitation as shown by cumulative biomass yield (Mg/ha) over 360 years with different rotation length and harvest type. Inputs of N through non-symbiotic N-fixation were assumed to remain constant at 0.5 kg N (ha $yr)^{-1}$.

	30 yr rotation		90 yr rotation	
Precipitation N inputs	stems only	whole tree	stems only	whole tree
2.0 kg N (ha $yr)^{-1}$	893	962	800	873
1.0 kg N (ha $yr)^{-1}$	800	850	714	776
0.5 kg N (ha $yr)^{-1}$	748	792	667	727

increase confidence in model predictions for older stand ages.

While FORCYTE-11 was able to correctly rank treatment stemwood and stem density at Shawnigan Lake for the 15-years of data available, the model was biased as to the effects of fertilization and thinning. This bias resulted from the divergence between model predictions and data as the stand aged. At later stand ages, this bias could eventually cause the model's rankings of treatment effects to significantly differ from actual rankings. Therefore, while model predictions were good in the short-term, extrapolation with the model to examine the effects of intensive forestry on long-term production over multiple-rotations could lead to erroneous predictions. Thus, while it is clear that the actual values predicted by the model should be treated with caution, it is uncertain, how well the model predicts, over the long-term, the relative impacts of different intensive forestry practices.

Even with such cautionary notes, FORCYTE-11's simulations of the effects of intensive management on long-term yields appeared plausible. The effects of short-rotation whole-tree harvest were similar to those described in other model simulations of different intensive forest management regimes, yield each rotation declining after several rotations. The reduction in yield after the first 90-year rotation was suprising, as other simulations of long rotations demonstrated either no long-term decrease in yield or only slow declines after several rotations. The reduction in the 90-year yield demonstrated the importance of the model's initial starting state, the two intense burns having dramatic impacts upon site productivity. Sachs (et al. 1989) found that in simulations of 30-year rotations in medium-site Douglas-fir in Oregon, moderate slash-burns caused yield to decline two rotations earlier than in unburned sites. FORCYTE-11 predicted that, at Shawnigan Lake, fertilization with high rates of N initially could ameliorate the effects of the burns. For later rotations, both of the 30-year rotations and the 90-year whole-tree regime, constant inputs of N were required to maintain yield, while the 90-year stems-only regime needed no fertilizer after the 3rd rotation. In all cases, the greater the N input, the greater the cumulative yield. The effects of N additions were also demonstrated in the model's sensitivity to N inputs from precipitation, emphasizing the need for knowledge on the amounts, sources and fate of N in forests.

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An Overview of IFMIS: the Intelligent Fire Management Information System[1]

B.S. Lee and K.R. Anderson[2]

ABSTRACT

The Intelligent Fire Management Information System (IFMIS) is a microcomputer based decision support system developed primarily for forest fire preparedness planning and for dispatching initial attack resources to wildfires. IFMIS integrates large data bases with spatial analysis techniques, linear programming, and expert systems to provide improved decision making for forest fire management. This paper is an overview of IFMIS and its application by forest fire management agencies in Canada and Alaska.

INTRODUCTION

Canadian forest fire management agencies in recent years have become more dependent on decision support systems for planning and real-time decision making. In western Canada, a number of forest fire management agencies have adopted forest fire preparedness planning approaches to determine daily initial attack resource requirements (Gray and Janz 1985; Lanoville and Mawdsley 1990). Forest fire preparedness planning is the process of ensuring that adequate suppression resources are available to cope with daily anticipated fire events. Until recently, preparedness planning was strictly weather based and did not incorporate fuels or topography. The Intelligent Fire Management Information System (IFMIS) offers a new approach by integrating weather, fuels, and topography into a spatially based procedure for forest fire preparedness planning. The spatial approaches used by IFMIS also improve real-time decision support for dispatching initial attack resources to wildfires by providing better estimates of fire weather and fire behavior potential.

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INTELLIGENT FIRE MANAGEMENT INFORMATION SYSTEM

IFMIS is a decision support system developed at Forestry Canada's Northwest Region (Lee 1990; Lee and Anderson 1990; Lee and Smith 1990). It was initially conceived as an expert system advisory tool for initial attack dispatching of fire control resources to wildfires. Since initiation of its development, however, it has slowly evolved to a full featured decision support system for forest fire management. Its success is no doubt in part due to the close cooperation and involvement of client agencies from the inception of the system to its operational implementation.

History

IFMIS has been under development since 1987 and was first demonstrated to the Alberta Forest Service at Whitecourt Forest, Alberta, Canada, in September of 1988 (Table 1). Since then, a total of six Canadian and one US agency have either adopted IFMIS or are evaluating its application within their organizations. The first operational trials of IFMIS were conducted in 1989. In that year four installations were tested in the Canadian provinces of Alberta and Saskatchewan. In 1990, six installations were added including four forests in Alberta, the State of Alaska, and Kootenay National Park. At least five more installations are being planned for the 1991 fire season. Figure 1 shows the areas of western Canada and Alaska where IFMIS is either currently being used or being considered for use.

Description

The system integrates a number of advanced technologies including: relational data bases, mathematical modeling, geographic information display, and expert systems. Lee (1990) described the conceptual basis and structure of IFMIS software as of the 1988 fire season. Since then, the PROLOG programming environment has been abandoned in favour of the more efficient C programming language. Also, the artificial intelligence work currently uses a hybrid expert system shell to deliver the expert system applications. To the user, however, the system is functionally the same as in the 1988 version. Since then, the spatial analysis procedure for forest fire preparedness has been added to enhance the planning capability of IFMIS.

Table 1: Table of IFMIS installations listing the year of installation, size of the protection area, the number of records in the cell data base, mean cell size, number of weather stations, the number of initial attack bases, and the number of air tanker bases. (Totals reflect only those installations identified by shading to prevent duplication of values.)

IFMIS Installation	Year	Area (km^2)	Cells	Cell Size (ha)	Weather Stations	Initial Attack Bases	Air Tanker Bases
Whitecourt Forest, Alberta Canada	1988	19,948	31168	64	14	19	1
Grande Prairie Forest, Alberta Canada	1989	49,028	76606	64	21	21	1
Province of Alberta Canada	1989	378,363	591192	64	208	214	15
Province of Saskatchewan Canada	1989	121,000	121000	100	43	41	5
Athabasca Forest, Alberta Canada	1990	42,454	66335	64	20	23	1
Bow-Crow Forest, Alberta Canada	1990	16,036	25056	64	14	14	2
Lac La Biche Forest, Alberta Canada	1990	32,850	51328	64	17	19	1
Slave Lake Forest, Alberta Canada	1990	55,132	86144	64	30	26	2
Kootenay National Park, Canada	1990	1,404	5616	25	3	5	0
State of Alaska, USA	1990	-	-	-	84	21	7
Province of Manitoba, Canada	1991	-	-	-	42	61	5
Eastern Region, Manitoba Canada	1991	-	-	-	6	7	0
Northwest Territories, Canada	1991	1,065,165	5525	19279	48	38	6
Hudson Bay Region, Sask. Canada	1991	-	-	100	5	6	1
Prince Albert Region, Sask. Canada	1991	-	-	100	9	8	1
Province of Ontario, Canada	1991	-	-	-	-	-	-
Totals		1,565,932	723,333		428	380	38

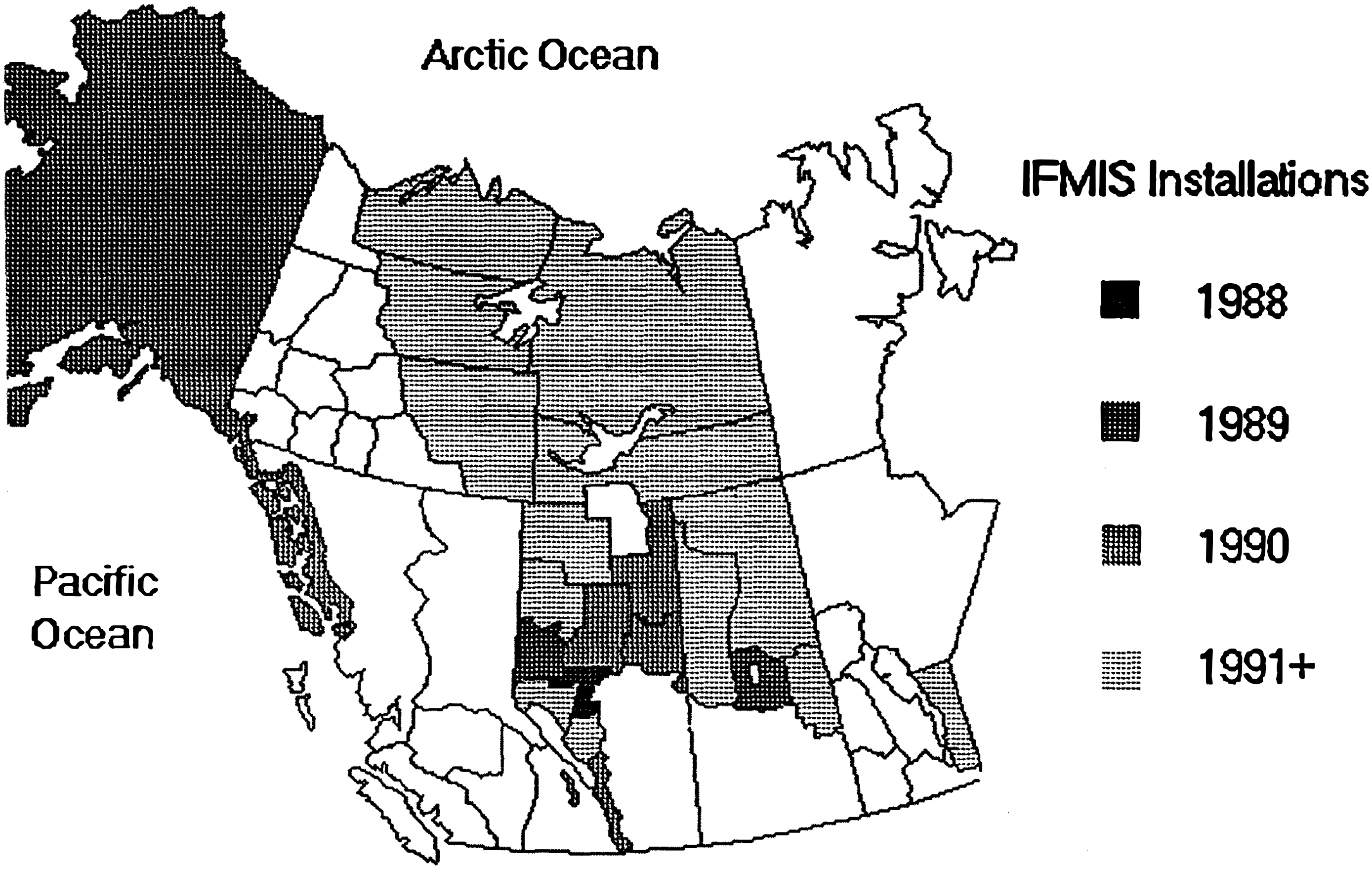

Figure 1: Map of IFMIS installations in western Canada and Alaska by year of establishment.

SPATIAL ANALYSIS

Fire management operations and planning is a spatial problem. In this respect, IFMIS has the ability to integrate and analyze spatial data such as weather, forest fuels, and topography (Lee and Anderson 1990). Central to this approach is the forest environment data base. This data base consists of geographically referenced cells containing forest fuel type, slope, aspect, and elevation information. The cell size depends on available data, with most IFMIS installations using cell sizes varying from 25 to 100 hectares (Table 1).

Using the forest environment data base, IFMIS applies models to predict the fire danger for each cell within a region. This approach can provide the forest fire manager with daily or hourly maps and reports depicting fire weather, fire behavior, and resource utilization effectiveness. IFMIS can produce these products on demand in a matter of minutes.

Fire Weather

IFMIS uses the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) as a basis for modeling and interpreting fire weather. The FWI System estimates forest fuel moisture conditions using empirical models driven by daily 1200 LST[3] weather readings. These weather readings include temperature, relative humidity, 10 metre wind speed, and precipitation. Outputs from the system include three fuel moisture codes and three fire behavior indices. Typically, the input data are collected from a network of fire weather stations using either manual or automated weather stations.

IFMIS can produce fire weather maps using a variety of interpolation schemes. The preferred approach uses a weighted moving average shown in the following equation,

$$x' = \frac{\Sigma x_i / d_i^2}{\Sigma 1 / d_i^2}$$

[3] Local standard time.

where x' is the interpolated weather value at a location x_i, and d_i is the distance from the location to the weather station (Figure 2a).

Fire Behavior

The Canadian Forest Fire Behavior Prediction (FBP) System has been in use in Canada since 1984 (Lawson *et al* 1985). The FBP system estimates the forward rate of spread (ROS) of a fire for a number of defined fuel classes using input FWI values. Additional FBP outputs include the head fire intensity (HFI), the crown fraction burned (CFB), and the total fuel consumed (TFC).

Using the FBP system with the forest environment data base and interpolated FWI values, IFMIS can produce maps of potential fire behavior such as ROS (Figure 2b), HFI, CFB, and TFC. This integration of interpolated weather with fuels and topography to produce quantitative estimates of potential fire behavior has greatly improved the ability of fire management agencies to respond to daily fire management planning issues.

Preparedness Planning

Lee and Anderson (1990) described a spatial approach to forest fire preparedness planning that incorporated weather, fuels, and topography to sub-optimally determine the daily allocation of suppression resources. Fire management planning in western Canada is based upon the philosophy of early detection of forest fires and rapid initial attack. In order to meet this goal, all fires must receive initial attack before they reach a critical size. This criteria is called the initial attack size objective. Using such a policy, IFMIS can assess the efficiency of pre-positioned resources within a forest region on a daily or hourly basis.

For each cell, IFMIS computes the time it would take a potential fire to reach the initial attack size objective. This elapsed time criteria, referred to as the attack time, can be displayed in map form (Figure 2c). With this type of information, the forest fire manager can use IFMIS to determine how many resources can reach the cell within this time from predetermined bases. This elapsed time includes both the get-a-way time and travel time to a cell. By selectively activating and deactivating initial attack bases, a coverage assessment map (Figure 2d) can be

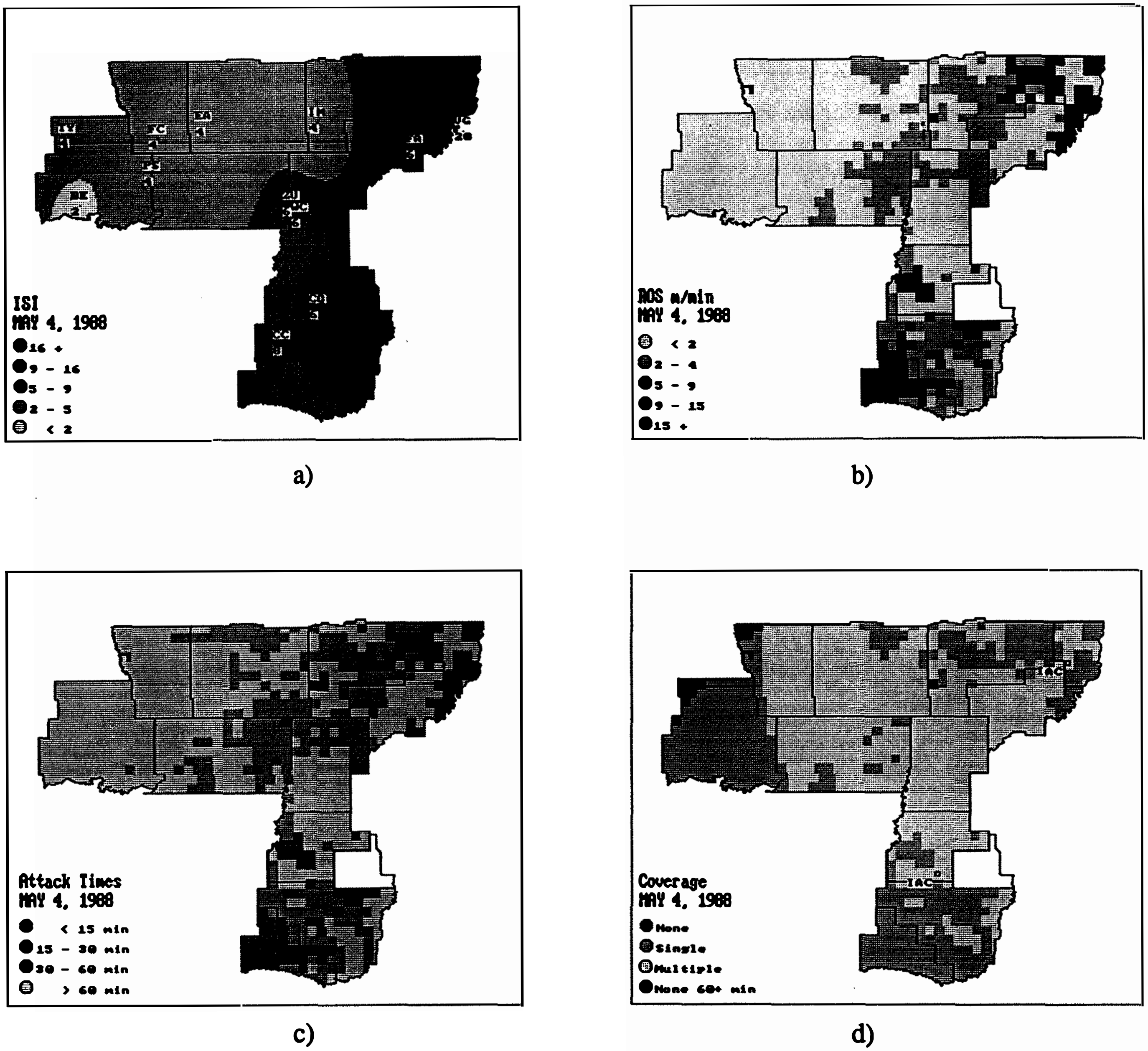

Figure 2: Examples of IFMIS map products showing (a) the initial spread index (ISI), (b) the head fire rate-of-spread (ROS), (c) attack times, and (d) initial attack crew coverage for May 4, 1988, Whitecourt Forest, Alberta Canada.

produced. Coverage for a cell is often classified as none, single, or multiple meaning that zero, one, or more than one initial attack resource can reach the cell within the attack time required. Those cells classified as no coverage are considered to have a higher probability for an escaped wildfire to occur given an potential ignition source.

DECISION SUPPORT

In order to extend the capabilities of IFMIS, research and development is currently being focused in two areas; mathematical modeling to determine optimal preparedness planning levels and expert systems for policy integration and initial attack dispatching.

Optimization

Building on the spatial analysis approach described by Lee and Anderson (1990) to determine the number of initial attack resources to be activated on any one given day, a linear programming approach has been developed to determine this information optimally. The methodology uses integer programming to determine the minimum number of initial attack crews or air tanker groups to activated on any one given day. In addition, the algorithm determines the optimal geographical positioning of these resources.

This initial attack resource allocation problem belongs to a class of integer programming problems called covering (Schrage 1986). The problem can be formulated as collection of demand points throughout the forest. These demand points are represented by the cell (fire environment) data base used by IFMIS. Initial attack bases and/or airports make up the supply points for the daily pre-positioning of air attack resources.

The decision variables are:

x = the initial attack bases

c = the daily cost of operating the initial attack base

a = a binary coefficient (0 or 1)

For j = 1,2,.....,n, define a zero-one variable x_j to designate whether or not initial attack base j is selected.

The optimization problem is to minimize the number of initial attack bases activated on any given day while ensuring the maximum cell coverage possible. The objective function for the formulation can be written as follows:

$$minimize \sum c_j x_j$$

subject to

$$\sum a_{ij} x_j \geq 1$$

where the coefficient a_{ij} equals 1 if cell i is covered by initial attack base j, otherwise it equals 0. Coverage is determined by comparing the get-a-way time plus the travel time from each initial attack base with the attack time. If the get-a-way time plus the travel time is equal to or less than the attack time, the coefficient a_{ij} is given the value of 1, else it is assigned the value 0. Cells in which no travel times meet the initial attack objective time are excluded from the analysis and are assumed to be not covered. The formulation incorporates the cost (c) of activating each initial attack base. If c is not available it can be considered to be the same for each initial attack base.

The current formulation of this problem looks only at the aspect of ensuring that initial attack resources will arrive at the cell prior to a fire reaching a certain size. The formulation does not consider the risk of a fire occurring within a particular cell within a given day. Also, the approach does not yet incorporate any containment modeling or resistance to control criteria. In spite of these limitations, the approach provides a good starting point to determine the initial attack requirements of a forest on any given day. An example of the output from the optimization algorithm is presented in Figure 3.

Expert Systems

Expert systems are computer programs that undertake the solution of complex tasks or problems using knowledge rather than data and by mimicking the solution methods of human experts. The knowledge embodied in an expert system may be that of one or more experts within a narrow field of endeavour. As such, expert systems are well suited to problems which

INITIAL ATTACK OPTIMIZATION

Initial Attack Crews:

Base	Aircraft	Status	Location
W20	206B	15 Minutes	Cold Creek R.S.
W43	206B	15 Minutes	Timeu

Figure 3: Initial attack optimization report for May 4, 1988, Whitecourt Forest, Alberta, Canada showing the requirement for two helicopter transported initial attack crews.

Appropriate suppression response expert system summary

Initial attack strategy: Direct and indirect attack

Fire intensity rank: 3

Low to vigorous fire behavior.
Hand prepared fire line likely to be challenged.
Heavy equipment may be required.

Special considerations:

Gas plant located at SE-13-19-58 W of 5

Recommended appropriate suppression response:

Helitack crew 1 from W14 Grizzly

Air tanker group 1 from Grande Prairie

Figure 4: Appropriate suppression response expert system summary for a hypothetical fire occurring on May 4, 1988, in the SW quarter of Section 1, Township 58, Range 18, west of the 5th meridian in the Whitecourt Forest of central Alberta.

are too imprecise to be defined in terms of mathematical models, although mathematical models may be used to derive facts for use in the knowledge base.

Current research and development work with expert systems is centred around encoding agency policies and human expertise into knowledge processing activities such as preparedness planning and recommending an appropriate suppression responses for new fire starts. A presuppression planning advisory system has been developed for Kootenay National Park which makes recommendations on how to deploy fire crews, when to charter or release rotary wing aircraft, and appropriate detection and prevention activities. In addition, an appropriate suppression response expert system has been demonstrated that recommends resources to be dispatched to new fire starts and the appropriate tactics to be used (Figure 4).

CONCLUSIONS

IFMIS was originally developed to be a cost effective decision support system for initial attack dispatching. Since its inception in 1987, it has gradually matured to a full featured fire management information system that has been adopted by seven fire management agencies in Canada and the United States.

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PRELIMINARY VALIDATION of "ONTWIGS": A FOREST PROJECTION SYSTEM ADAPTED for ONTARIO

B. Payandeh and P. Papadopol

ABSTRACT

"ONTWIGS" is an adaptation of the "LSTWIGS": a growth and yield projection system developed for the Lake States. Because of similarities of growth conditions in the Lake States and Ontario, "LSTWIGS" was modified for use in Ontario. This involved input/output metrification, species codes and model coefficients substitution, where necessary. Preliminary validation results with black spruce stands from northern Ontario and red pine plantations from Ottawa valley indicate that, in the absence of any local projection model, "ONTWIGS" may be used as an adequate growth and yield projection system for short to medium projection periods.

Validation Data and Statistics

The data used to validate "ONTWIGS" so far consist of 77 permanent sample plots (points) from peatland black spruce in northern Ontario and two 0.2 ha (1/2 acre) plots red pine plantations from Rockland, Ontario. The black spruce plots were remeasured in five years while those of the red pine were remeasured ten times during the 48, year period. One of the red pine plots was thinned in 1938, 1951 and 1961. Individual tree data was expanded to per hectare basis as required by "ONTWIGS". Data from each plot was considered as a tree list. Ingrowth trees were added, thinned trees were removed from the tree list based on the remeasurement data. The important stand characteristics used for validation were: a) quadratic mean diameter (QDBH), representing tree growth, b) number of trees/ha (TPH), as a measure of tree survival, and c) basal area/ha (BAH) as a measure of overall system performance.

SUMMARY and CONCLUSIONS

Results indicate that "ONTWIGS" overpredicted tree survival, QDBH, and BAH of black spruce by 12% 4% and 15%, over a five year period. For the unthinned red pine plantation "ONTWIGS" on average overpredicted survival, QDBH, and BHA by 14%, 4% and 20% over a five year projection period. However, for the entire 48 year period the model overpredicted survival by 19%, and basal area by 13%, but underpredicted QDBH by only 2%. Result for the thinned plantation were surprisingly close to the observed data, where the model overpredicted survival, QDBH, and BAH by 1%, 2% and 6% over a five year period, respectively. For the entire projection period the model performed extremely well by overpredicting survival BAH by only 3% and 2%, respectively and underpredicting QDBH by only 1%.It may be concluded that, "ONTWIGS" may be used as an adequate growth and yield projection system for black spruce for short projection periods and for red pine plantations for periods as long as 30 to 50 years.

POINT-DENSITY ESTIMATION WITHIN BLACK SPRUCE/ BALSAM FIR SEEDLING POPULATIONS[1]

P.F. Newton
Newfoundland and Labrador Region,
Forestry Canada, St. John's, Newfoundland

SUMMARY

Regeneration assessment on recently disturbed sites is an essential component of stand-level management planning. Recently a fixed-precision list-quadrat sequential sampling system for estimating point-densities within black spruce (Picea mariana (Mill.) B.S.P.)/balsam fir (Abies balsamea (L.) Mill.) seedling populations was developed. Specifically, the key determinate of the sampling system was the equation expressing the variance of seedlings per quadrat (σ^2) as a function of the mean seedling count per quadrat (m). Three functional forms proposed for biological populations were evaluated using seedling count-data derived from 43 0.121-ha sample plots located within central insular Newfoundland. Results indicated that a power law relationship best described the σ^2-m relationship within the seedling populations analyzed. Employing this relationship, a fixed-precision list-quadrat sequential sampling plan was constructed for operational use.

[1] Newton, P.F. 1989. Fixed-precision list-quadrat sequential sampling for point-density estimation. Forest Ecology and Management 27: 295-308.

Bella, I.E.; Ejsmont, M.; Navratil, S.; Yang, R.C. 1990. Developing a decision support system for aspen stand management in western Canada. A Poster.

Abstract

A decision support system (DSS) which synthesizes fragmented research results, operational knowledge and heuristic rules into an integrated knowledge base is currently under development at NoFC. The system will support decision making on harvesting, regeneration, tending, yield and product forecasting at the stand level and provide financial analysis. Interfacing with GIS and incorporating knowledge bases on wildlife, ecological site, and inventory will link the Aspen DSS to the Mixedwood Management DSS and will facilitate decision-making at the forest level.

FORESTRY CANADA MODELLING WORKING GROUP

Notes from Meeting at Kananaskis, December 14, 1990

by Jim Richardson

Present: B. Payandeh (chair), M.J. Apps, R. Swanson, I.E. Bella, P. Newton, P. Papadopol, G.M. Bonnor, R.M. Newnham, J. Richardson, H. Grewal, T.A. Trofymow.

1. Regional Summaries

a. HEADQUARTERS - J. Richardson

Reorganizations within Science Directorate:

DG - Fred Pollett

Director, Science Policy - Graham Page

Coordinators - Gus Steneker, Guy Brassard

Director, Protection - Les Carlson

Coordinators - Ben Moody, Pritam Singh

Acting Director, Environment - Dennis Dube

Coordinators - Peter Hall, Ole Hendrickson

Acting Director, Forest Resources - Jim Richardson

Coordinators - Bill Cheliak (till March 31, 1991)
Tim Boyle (from January 1, 1991)

Science Directorate now has a budget for Working Group activities. It is intended to support specific WG projects or to help bring outside speakers to WG meetings. It is not to be used to cover travel costs of WG members to meetings.

b. ONTARIO REGION - Bijan Payandeh

Entomology - 3 modellers were working, principally on modelling insect population dynamics - Nealis, Lyons, Lysyk. Lysyk left 18 months ago and his position has not been filled.

Fire - Lynham is working on modelling people-caused fires with Martell (U of T) - data had to be reanalysed. There is cooperation with PNFI, OMNR, USFS and NASA.

Silviculture - Groot is back from PhD studies at Guelph and is working on physically-based models for predicting microclimates in clearcuts - he is collecting data for calibration. Fleming is back from PhD studies at UBC and is working on direct seeding of black spruce in northern Ontario, developing stochastic models of germination, growth, and mortality of seedlings in relation to site preparation. He is also working on biophysical studies of site preparation with respect to seedling response to site preparation and evapotranspiration, leading to the development of a site water-balance model and a model of seedling stomatal response to environmental conditions.

Growth and yield and regeneration - Payandeh was off for a while following a heart attack but is now back calibrating ONTWIGS and finalizing the regeneration model (with Punch) with a user manual. The economic analysis model (FIDME) has been modified. Program is being restructured and reoriented towards work on development of forest management systems for major timber species of Ontario.

LRTAP - Morrison's study of organic matter distribution and cycling is complete. He is trying to get into nutrient cycling modelling.

Economics modelling - Andersen.

c. PNFI - Monty Newnham

Dave Brand is now confirmed as manager of the Forest Management Systems Project.

The silviculture and soils/nutrition projects have been merged under Darwin Burgess. Guy Laroque is now part of this group.

Fire management systems - much technology transfer is going on, as well as conversion of computer systems to C and Suns. Peter Kourtz is involved in AI and neural networks.

Brand's regeneration modelling work has gone to a consultant for technology transfer.

Artificial vision and robotics are being explored for silviculture and harvesting machinery.

Jack pine budworm management model - Mike Power is at Texas A&M, and the modelling effort involves cooperation with USFS and Texas A&M.

LOGPLAN - Newnham

Harvest Schedule Generator model (Tom Moore) - has been published. He is now looking at the adjacency problem in harvest scheduling, using the annealing algorithm.

Object-oriented programming is being explored, using 'Smalltalk'.

PNFI now has 9 Sun workstations networked.

Laroque's PhD thesis is nearing completion.

d. NORTHWEST REGION - Imre Bella & Mike Apps

Climate change modelling, carbon balance - Mike Apps

Decision support system for aspen-mixedwood is one of the top research priorities at NoFC. A knowledge-based, goal-oriented system is planned. This is expected to be a long-term project. Work on this will be done as a team.

December 14 is Ross Waldron's last day as program director. He is expected to be succeeded by Ian Corns.

Hydrology modelling - Swanson - WRENSS - major use is being made of this - also HSPF. He wants to work with FMA's in northern Alberta. Also involved with transpiration modelling in support of climate change work.

Regeneration modelling - Stan Navratil

Insect modelling - Jan Volney is involved with the jack pine budworm modelling effort.

Growth and yield - Bella and Chris Ciesewski (who is presently working on a PhD at U of A on mixedwood growth modelling) - regional growth and yield prediction for all common species.

FORCYTE-11 is now complete. The FORCYTE-11 manual and code are "out". A PROBE manual is in preparation. The FORCYTE-10 manual in nearly complete and will be PROBE-linked.

Apps is looking at FORET-JABOWA types of models for ecosystem succession in connection with climate change work.

Harjit Grewal is involved with using FORCYTE-11 for mixedwood forest management. He is also beginning to study climate change effects on forest dynamics and productivity using LINKAGES.

Teja Singh is working with the university and Saskatchewan Research Council on risk analysis modelling, with particular reference to climate change.

IFMIS - Bryan Lee. de Groot will work on future response of the forest fire sector in light of climate change.

Site classification and site mapping - Ian Corns. The work is GIS-related and productivity related.

Policy framework modelling - towards integrated forest resource management. This is in the planning stage - Diana Boylen.

In general, modelling work at NoFC has expanded in the last year.

e. PACIFIC & YUKON REGION - Mike Bonnor & Tony Trofymow

Restructuring - the Shawnigan Lake project has been split with the growth and yield aspects being retained in the growth and yield project and the process-oriented aspects being disbanded.

Growth and yield - now known as "Fibre Production". A stand-type model is being developed for inventory update, timber supply analysis, etc. It will cover all stages from establishment to harvest and will use minimal input data. Bonnor has a western hemlock dataset to develop the model structure and will then move to other species. This work is in direct response to direction from the Productivity Councils.

Pest modelling - Rene Alfaro is working particularly on defoliators and their effects on growth, mortality and quality.

The interior Douglas-fir study is to be wrapped up.

A guide and survey is being conducted for the Productivity

Councils regarding on-going activities in growth and yield. This will describe modelling procedures being used and establish a common terminology.

Eleanor McWilliams (nee Gardner) is now back from the University of Minnesota.

Al Thomson has had many requests for expert systems help. He is working on nursery pest identification systems (with Jack Sutherland).

Ross Benton is working on extrapolation of weather data.

Shawnigan work is broadening to look at a chronosequence of sites (both older and younger than Shawnigan Lake) with respect to the fate of C and N in relation to stand development. Work is also being done on carbon in the litter of old-growth forest.

Hugh Barclay - host-parasite and pheromone modelling.

Tony Trofymow - soil water balance model calibration completed, and now working on a layered model. Also working on a decomposition model with respect to soil physical conditions.

f. NEWFOUNDLAND & LABRADOR REGION - Peter Newton

Newton has been at UBC on PhD studies for 1 year now, working on yield-density management modelling for black spruce.

In the forthcoming new FRDA there will be $150K for direct delivery of growth and yield research. There are two proposals for using this: Lavigne would like to hire someone to compile and format all existing Newfoundland growth and yield data, including thinning trials, and evaluate models to use this data; Newton prefers a dual approach and would also accelerate work on existing modelling efforts so that they reached completion.

Dobesberger, who was working on insect modelling, and spruce budworm sampling designs, has left.

2. Next Meeting

Payandeh proposed that the next working group meeting be held in Sault Ste. Marie August 20-22 in conjunction with meetings of the Midwestern Forest Economists, Midwestern Forest Mensurationists, Great Lakes Growth and Yield Coop, and possibly CPPA. The

Modelling Working Group would contribute to the other meetings and hold a separate business meeting. About 140-175 people could be expected in total. Advertising of the whole event would be done jointly. Payandeh will organize the event and expects to have an announcement out in February.

The members agreed to the proposal. There was some discussion regarding publication of the proceedings. The Midwestern Mensurationists do not normally publish their proceedings, but inclusion of papers could be put on a voluntary basis. Proceedings could be funded from the Working Groups budget.

3. National Growth and Yield Study Proposal

Mike Bonnor proposed a coordinated national growth and yield modelling effort to which all Forestry Canada establishments could contribute. The Modelling Working Group would coordinate the study. An overall national modelling framework could be developed, with respect to AAC calculation, for example, and each establishment could add components as desired. The study would require funding which might come from S&T Funds, though it is too late for 1991-92. The proposal met with interest and it was agreed to pursue it. Bonnor agreed to take the lead (subject to his management approving) and will develop and circulate a concrete proposal. The intention was that the plan would be ready for final endorsement at the time of the August 1991 meeting.

Similar coordinated efforts could be considered in the areas of carbon balance and climate change modelling.

4. Proceedings

Harjit Grewal will coordinate the preparation of the proceedings of the 1990 meeting. Papers should be sent by electronic means as well as in hard copy. Business meeting minutes and regional reports will be included. Deadline for receipt of copy is January 15.

The proceedings of the 1989 meeting are now out. Members should ensure that all libraries get a copy.

5. A hearty vote of appreciation was registered for the organizers of this successful meeting, particularly Harjit Grewal and Mike Apps.

Forestry Canada 5th Modelling Workshop Summary Update for Ontario Region

by Bijan Payandeh

A) Entomology: Vance Nealis and Barry Lyons are continuing their work in entomological modelling as reported last year. The insect population dynamics position vacated by Tim Lysyk has not been filled as yet. Therefore most things remain pretty much the same as reported in the last meeting.

B) Forest Fire: Tim Lynahm is continuing on his joint study with Dave Martell of University of Toronto on modelling people-caused forest fires. Apparently they have discovered some major discrepancies in the data received from Ontario Ministry of Natural Resources. This required reanalysis of the data thus causing delay in publication of the results. Other cooperative studies with PNFI, OMNR, US Forest Service and NASA have continued.

C) Silviculture: 1) Art Groot who recently returned from educational leave from university of Guelph has been working on a physically-based model for prediction of forest clear-cut microclimate as his Ph.D. Thesis. He has developed such a model to examine the effect of site properties such as organic matter depth, soil type, and aerodynamic roughness length on forest clear-cut microclimate. The model comprises of a numerical solution of the one-dimensional transfer equations for energy and water in the soil and air near the surface of forest clear-cuts. Required boundary conditions include incoming radiation, air temperature, water vapour pressure and wind speed at a reference height, soil temperature and water potential at a reference depth, and rainfall. The model is applicable to flat, sparsely vegetated, uniform surfaces of considerable horizontal extent. Microclimate data were collected on three forest clear-cuts in northeastern Ontario during 1989 and 1990 to meet model predictions. Comparison of predicted and measured air temperature, water vapour pressure, soil temperature, and soil water content is currently underway.

2) Rob Fleming has also returned from educational leave at UBC. He is currently working in two areas of direct seeding of black spruce in northern Ontario and biophysical studies of site preparation in the southern interior of British Columbia. With the seeding work he is developing a stochastic model to examine relationships between germination, growth and mortality, and seedbed, site and climate. Stocking, clumpiness and seedling-seedbed distribution relationships are of particular importance. The biophysical studies of site preparation have two modelling components of: a) the site water balance and moisture availability, and b) stomal response of seedlings to environmental conditions. Climatic conditions and periodic measurements of soil water content and potential are being used as to examine the performance of simple evapotranspiration models. In addition a two or three dimensional numerical model is being considered to investigate the effects of scarification on soil moisture and temperature as a function of distance from scarification boundary. A multiplicative, boundary - line analysis model is currently being developed to study the

stomal response of Douglas-fir and lodgepole pine seedlings to physical soil and atmospheric variables. This phenomenological model should predict the effects of climate and site preparation on seedling stomatal conductance and transpiration.

D)Growth and Yield and Regeneration: As a result of my heart attack last April, the work on black spruce growth and yield study has slowed down considerably, however, calibration of the "ONTWIGS" model is now in progress and an economic feasibility of forest drainage fertilization and/or thinning will be conducted as a "wrap up" work on this study by next year. Considerable progress has been made in developing, testing and calibration of "Plant PC" and its demonstration to forest managers and other potential users. Mike Punch is currently preparing a users manual for the model as the final requirement for his COFRDA contract. The model should be ready for release and distribution by next March. "FIDME PC" has been modified somewhat to allow for input file editing and manipulation. It will be used for the final economic analysis mentioned above for the growth and yield study wrap up and yield study. Following restructuring of two research projects: Black Spruce and Reforestation Silviculture, proposals for developing forest management advisory systems for major forest types in Ontario are underway.

E) LRTAP Project: Ian Morrison has recently finished a study on organic matter distribution and cycling at Turkey Lake, near Sault Ste. Marie. Neil Foster attended the University of New Brunswick last summer to familiarize himself with modelling methodology and approaches in nutrient cycling. Following is a sample of publications related to modelling efforts at Ontario Region.

This basically summarizes modelling activities at Ontario Region during last year. I have noted a number of related publications and reports in my summary.

Related Publications

Morrison, I. K. 1990. Organic matter and mineral distribution in an old-growth Acer saccharum forest near the northern limit of its range. Can. J. For. Res. 20: 1332-1342.

Morrison, I. K. Addition of organic matter and elements to the forest floor of an old-growth Acer saccharum forest in the annual litterfall. Can. J. For. Res. (in press).

Nealis, V. G. 1990. Jack pine budworm populations and staminate flowers. Can. J. For. Res. 20: 1253-1255.

Payandeh, B. 1990. Equations describing attributes of major tree species in north central Ontario. For. Ecol. Manage. 36: 245-252.

Payandeh, B. Development of a model for planting stock production evaluation in Ontario. Submitted to the New Forests.

Payandeh, B. Composite site productivity functions for northern Ontario black spruce. Submitted to the New Forests.

Payandeh, B. Plonski's yield tables (metric) formulated. submitted to the Forest. (In Press).

Payandeh, B. and L. N. Huynh. "ONTWIGS" A stand growth projection system adapted for Ontario. Intended for Info. Rep. (In Press).

PFC Modelling Activities 1989-90

by Mike Bonnor

1. The growth and yield project is currently called the Fibre Production Subprogram but restructuring is still going on so the name may change. Principal researchers: Bonnor, McWilliams, De Jong.

Activities in the Subprogram are:
- Development of a stand growth model, with an imbedded diameter distribution model, is the main task. It is intended for inventory update, AAC calculations and timber supply estimation at the regional level. It will be implemented first for western hemlock, later for interior species (aspen?).
- Continued pest modelling by Rene Alfaro;
- Continuation of the mensurational component of the Shawnigan research project (Effects on growth and yield of thinning and fertilization of Douglas-fir). Process oriented aspect has been abandoned.
- Assessing growth of Interior Douglas-fir, and developing a diameter matrix model, is largely completed. Reports in preparation.
- For the B.C. Productivity Councils, we are producing a "Guide to growth model types and applications" and undertaking a "Survey of growth model uses and needs in B.C."

2. Eugene Hetherington:
The hydrology computer simulation model HSPF, obtained from the U.S. Environmental Protection Agency, was installed on the VAX and checked using test data provided. The intention is to calibrate it with Carnation Creek data.

3. Al Thomson:
Is developing expert systems for diagnosis and treatment of forest nursery problems. He has also just completed a variable-density lodgepole pine stand growth and mountain pine beetle impact model. His forest level mountain pine beetle spread model is currently under operational testing by the B.C. Forest Service.

4. Tony Trofymow:
Completed calibrating and testing FORCYTE-11 for Shawnigan Lake (report to be published as a BCX report and in the proceedings of the Modelling Workshop). Currently working on two modelling activities leading towards the final goal of a general soil model. The first is to modify, calibrate and test a water balance model for coastal Douglas-fir. The second is to implement and/or develop a variety of soil decomposition and nutrient mineralization models and then calibrate them against some specific results from controlled experiments. The final goal is to combine the abiotic and decomposition models and use them to predict rates of soil processes in the field.

5. Hugh Barclay:
- investigated the interaction of odour baited traps and pheromone baited traps for insect

pest control;
- investigated optimal combinations of methods of pest control to minimize cost of application;
- modelled Mountain pine beetle population dynamics with a view to identifying optimal control procedures;
- modelled pheromone release for mating confusion;
- modelled control of Spruce weevil by means of a combination of trapping and inundative parasitoid release.

Modelling activities at Laurentian Forestry Centre, Quebec Region

by Pierre Bernier

There are currently three modelling efforts under way at the Laurentian Forestry Centre. The first one is the work on spruce budworm population dynamics by Dr. Jacques Régnière. One of the more practical goals of this work is to provide forest managers with forecasts of budworm population levels as an aid in decision making. The modelling effort is viewed as a important component of an integrated pest management strategy for the budworm.

Modelling is also being carried out in the field of wetland drainage. Mr. Jean-Louis Belair has been using a modelling approach to understand the fluctuations in the water table of his instrumented wetland under various meteorological and drainage conditions. Wetland drainage, through its effect on water table, also affects tree growth. The next phase in Mr. Belair's work is therefore to incorporate in his model the water relations/tree growth interactions.

Dr. Louis Archambault, Mr. Robert Allard and Mr. Jacques Morissette are currently in the validation phase of an expert system for the diagnostic of biotic and abiotic health problems in red pine plantation. The expert system has been adapted by Mr. Robert Allard from earlier work done in the US on Wisconsin plantations.

STUDY:

National Wood Supply Study - Phase II: An Empirical Analysis of Regional Industrial Wood Supply and Demand.

PARTICIPANTS:

Dr. K.L. Runyon - Senior Socio-Economic Analyst
Maritimes Forestry Centre, Fredericton

Dr. D.L. Booth - Senior Economist, Resource Analysis
Economics and Statistics Directorate, Ottawa

Mark Messmer - Forest Economist
Maritimes Forestry Centre. Fredericton

Kevin Porter - Senior Programmer/Analyst
Maritimes Forestry Centre, Fredericton

SUMMARY OF ACTIVITIES:

Over the last year, a simulation model originally developed by Dr. Doug Williams (Cortex Consultants, Inc.) known as the Price Responsive Timber Supply Model (PRTSM) has been developed to produce supply curves for industrial roundwood for six regions in Canada, namely the B.C. Coast, B.C. Interior, Prairies, Ontario, Quebec, and the Atlantic.

The PRTSM simulates over time, the responses of industrial wood supply to a variety of cost, value, and regional policy variables. PRTSM can be "linked" with final product demands, to produce an overall supply-demand balance over time.

The first step is to link estimates of delivered wood cost with the inventory information. Analysis units with similar species, growth and yield and cost characteristics are formed. These analysis units are then "grown" over time, and estimates of the operable land base and sustainable supply levels can be made under various assumptions about future conditions.

Some initial work is under way for the B.C. and Atlantic regions.

For further information on the National Timber Supply Study please contact:

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LIST OF ATTENDEES (alphabetical order)

1	Mike Apps	Forestry Canada, Northwest Region, Edmonton
2	Imre Bella	Forestry Canada, Northwest Region, Edmonton
3	Mike Bonnor	Forestry Canada, Pacific & Yukon Region, Victoria
4	Chris Cieszewski	Forestry Canada, Northwest Region, Edmonton
5	M. Ejsmont	Forestry Canada, Northwest Region, Edmonton
6	Harjit Grewal	Forestry Canada, Northwest Region, Edmonton
7	George Host	University of Minnesota, Nat. Res. Res. Ins. Duluth, MN
8	Bryan Lee	Forestry Canada, Northwest Region, Edmonton
9	Dan MacIsaac	Forestry Canada, Northwest Region, Edmonton
10	Ralph Mair	Forestry Canada, Northwest Region, Edmonton
11	David Morgan	Alberta Forest Service, Measurement Branch, Edmonton
12	Stan Navratil	Forestry Canada, Northwest Region, Edmonton
13	Monty Newnham	Forestry Canada, PNFI., Chalk River
14	Peter Newton	Forestry Canada, Newfoundland & Labrador Region, St. John's
15	Pia Papadopol	Forestry Canada, Ontario Region, Sault Ste. Marie.
16	Bijan Payandeh	Forestry Canada, Ontario Region, Sault Ste. Marie.
17	Jim Richardson	Forestry Canada, Science Directorate, Ottawa
18	Teja Singh	Forestry Canada, Northwest Region, Edmonton
19	Bob Swanson	Forestry Canada, Northwest Region, Edmonton
20	Steve Titus	University of Alberta, Faculty of Forestry, Edmonton
21	Tony Trofymow	Forestry Canada, Pacific & Yukon Region, Victoria
22	Richard Yang	Forestry Canada, Northwest Region, Edmonton