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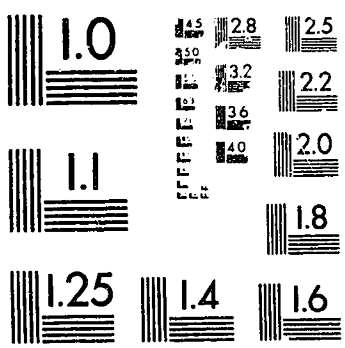
NBS 1010a ANSI/ISO #2 EQUIVALENT



University of Alberta

Spatial Optimization For Timber Supply With Spatial Constraints

By

Huili Liu ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of requirements for the degree of **MASTER OF SCIENCE.**

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To:

My family

ABSTRACT

This paper presents a spatial optimization model and algorithm for timber supply. This model consists of a single objective, Maximum Annual Allowable Cut (AAC) or Maximum Period Allowable Cut (PAC), with both multiple spatial and non spatial constraints that include non adjacency, exclusion period (or green up), maximum opening size, minimum cut block size, evenflow timber harvesting, and priority rule for selecting harvest stands. This model concurrently dynamically "blocks" and "harvests" the forest and is appropriate for both long and short planning horizons.

This spatial optimization is not a classical linear programming. Its algorithm is designed on the basis of the dynamic characteristics of tree harvest and growth, the golden (0.618) search method, and grid-based data structure. This algorithm is developed to interface with GIS ARC/INFO and is programmed by C++ and ARC Macro Language (AML) to automatically implement the spatial data input, spatial analysis and outputs with maps. The spatial optimization is applied to a sample dataset and the timber supply analysis and planning for four planning horizons are produced. The related discussions are focused on the effects of spatial constraints on timber supply, and the possible relationships among spatial optimization for timber supply, silviculture and biodiversity.

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Introduction

1.1 A Challenging Topic

Modern forest management operates in a complex dynamic economic, political, and biological system. For long term planning, the basic forest unit, the stand, is dynamically changed by cutting and growth. The spatial distributions of forest stands, split or grouped into cut blocks, may be constrained by limiting maximum and minimum opening sizes, by constraining the timing of harvest of adjacent cut blocks to be greater than some exclusion period or green up time, by the size of harvest proposed, and by imposing constraints on harvest flow over time, such as evenflow harvest. Therefore, forest harvest plans are focused on *where to cut and when to cut in order to best achieve goals such as net revenue and timber volume subject to these spatial and non spatial constraints*. Often, the spatial constraint levels are set by government regulations or company policy. Policy makers need to be able to estimate effects of setting various constraint levels on timber supply. Thus a model is needed which will find spatially explicit solutions for optimum timber supply with spatial and non spatial constraints.

1.2 Brief Overview

Most of the traditional optimization models are based on the linear or nonlinear programming methods (Buongiorno and Gilless 1987, Newnham 1991, Hoekstra *et al.* 1987, and Dykstra 1984). These methods played an important role in forest management planning in the past decades. However, as mentioned in the section 1.1, spatial constraints are increasingly recognized as being important concerns that must be involved in management planning (Torres-RoJo and Brodie 1990, Nelson and Finn 1991, Clements *et al.* 1990, *etc*). In order to examine spatial concerns, many investigators have developed models and algorithms to examine alternative harvest schedules for a pre blocked forest landscape, or developed a blocker algorithm which blocks the forest prior to application of a harvest schedule algorithm to harvest the forest within constraints. Recently, the leading developments for spatial optimization are focused on using binary (0-1) variables to represent each cut block and developing linear and nonlinear programming applications (Hof 1993, Hof and Joyce 1993, O'Hara *et al.* 1989, Roise 1990, Nelson and Finn 1991, *etc.*). However, the binary methods used dramatically increase number of the basic variables (which may be estimated by number of stands in the forest times planning horizon length divided by period length) (Daust and Nelson 1993). For example, for a planning horizon of 100 years using a period length of 5 years and a forest area of 1000 stands, the number of variables in the spatial model may be in excess of 20,000. Many algorithms for these spatial optimizations, such as Monte Carlo integer programming (Nelson *et al.* 1988 and O'Hara *et al.* 1989), biased sampling search technique (O'Hara *et al.* 1989) and hierarchical approaches (Weintraub and Cholaky 1991, and Wismer 1971), have been developed and used. Minimizing the number of adjacency constraints for linear optimization models was studied (Jones *et al.* 1991). And also the comparison and testing for these approaches are investigated (Jamnick *et al.* 1993, Nelson and Brodie 1990, and Clement *et al.* 1990). Although spatial optimization techniques have been dramatically improved, optimal evenflow timber volumes for planning horizons over a rotation length are a problem and how to significantly simplify the procedure and formulation of non adjacency constraints to achieve accurate solutions still exists. In all the spatial models, pre-blocking of the forest is needed to deal with the constraints of the maximum and minimum opening sizes, which is an added level of complexity for planning. Thus, in situations where sustainable timber supply is emphasized, existing LP models do not produce spatially explicit solutions for reasonable sized actual forests.

Many of the existing mathematical programming approaches are focused on spatially scheduling timber harvests for a real forest subject to spatial constraints. These approaches mainly include (1) integer programming; (2) mixed-integer programming; and (3) non-linear programming. Integer programming solves problems with integer variables (Zionts 1974 and Hof *et al.* 1994). Due to spatial timber supply requiring area-based allocation, binary variables are frequently used in developing spatial models. Mixed integer programming is used to solve a problem in which some but not all variables are integer variables (Zionts 1974 and Hof and Joyce 1993). Non-linear programming is a method which handles a problem with non-linear objectives or non-linear constraints (Vajda 1974 and Hof and Kent 1990). Because timber supply has explicit dynamic characteristics and also involves random yield, dynamic programming (Larson and Casti 1978) and stochastic programming (Sengupta 1972 and Hof *et al.* 1988) will be developed for spatial timber supply.

1.3 Objectives

In order to achieve a spatial optimization for timber supply on a reasonable sized actual forest, this paper presents a new spatial optimization model and algorithm. This model can quickly, concurrently and dynamically delineate block configuration and harvest rates for the forest over a planning horizon and maximize allowable cut, subject to the spatial and non spatial constraints including non adjacency / exclusion period, maximum and minimum opening sizes, evenflow timber harvest and a priority rule for selecting harvest stands.

The algorithm, based on the characteristics of grid-based data structure, is developed by using the golden (0.618) search technique (Mital 1983) and also is programmed by using C++ programming language and ARC Macro Language (AML). For convenience, *this Grid-based Spatial Optimization Model will be referred to as G-SOM.*

Unix ARC/INFO is interfaced with the model to provide the initial input spatial data for the model to use and to accept output data from the model in order to provide maps and tables of future simulated forests.

2
Functions of G-SOM

This chapter will highlight functions of G-SOM on spatial analysis and planning for timber supply. These functions may include or support (1) use of existing forest data; (2) management intensity; (3) policy options; (4) spatial estimation of timber volume; (5) maximum timber supply and spatial harvest schedule.

2.1 Use of Existing Forest Data

Spatial analysis and planning for timber supply are based on using existing forest data including spatial (or geographical) data and attribute data. In this study, existing forest data consist of locations of stands and attributes of these stands including site class, species composition, and tree age. Yield tables (growth functions) for existing stands must also be available.

Site class

Site class is identified by site classification defined as a mean of grouping forest sites according to their capability of growing trees (Gessel 1986). Wide attention has been placed on site classification (Doucet and Weetman 1990, Clutter, *et al.* 1983, and Daniel *et al.* 1979). G-SOM requires a site classification that can be used directly with the yield table classes.

Species composition

Forest stands can be classed into pure or mixed species (Daniel *et al.* 1979). G-SOM requires species classes which can be used directly with yield tables. Examples might be species like pine or spruce or mixed species yield tables.

Tree age

A stand in a forest may have an even-aged or uneven-aged structure. In our case, tree age on each stand is determined on the basis of even-aged identification. Even-aged identification means seeking to establish a forest with a series of stands, each of which contains equal- or about equal-aged trees. G-SOM uses tree age for each forest stand which is one of the independent variables used with yield tables to get volume per ha estimates for that stand and thus G-SOM can not handle uneven-aged management.

Yield tables

Forest stands in G-SOM are grown over time by use of yield tables. Yield tables are expressions of volume per unit area as a function of site class, species composition, and tree age. Yield tables for both existing stands and for regenerated stands are required by G-SOM. Management actions regarding silvicultural prescriptions or options must be expressed in the yield table values or timing of these values if their actions are to be shown or demonstrated by G-SOM.

2.2 Management Intensity

Silviculture is the theory and practice of controlling forest establishment, composition, structure and growth (Spurr and Barnes 1980, Zasada 1990, and Sanders and Wilford 1986). G-SOM provides regenerated stand options regarding (1) regeneration lag; (2) site improvement; and (3) species composition control, which permit the user to simulate many silvicultural options.

Regeneration lag

Regeneration lag is a time interval between time right after a site is harvested and time when this site starts to grow new trees. Regeneration lag reflects the time for site preparation or site treatment. By use of a regeneration lag of opposite sign from about this feature can be used to simulate one cut shelterwood or understory protection (see Appendix D). G-SOM uses a regeneration lag specific for each site / species classification.

Site improvement

Incentives for regeneration are usually economic, social or environmental in those countries that have limited timber resources compared to the demand for these resources (Daniel *et al.* 1979). To ensure and improve the rapid establishment of vegetation, site preparation is often used to create a favorable condition for desired vegetation or create an unfavorable condition for undesired plants. Site improvement is based on ecological, physiological, managerial, and social factors (Daniel *et al.* 1979). G-SOM permits the simulation of management inputs after initial harvest to change the site class for regenerated stands. This could happen, for example by using genetic improved stock or intensive site preparation and fertilization. This option could also be used negatively to simulate a loss in site productivity that might result due to poor operational procedures.

Species composition control

Management goals should be set regarding species selection for new forest after harvest. Usually, one or more of the original species on the harvested sites are selected as a new tree species composition (Klinka *et al.* 1990). G-SOM permits regenerated stands to be any species represented by a regenerated yield table which is controlled by the management decision of "what to regenerate".

2.3 Policy Options

Policy options consist of (1) selecting a planning horizon and a period length; (2) selecting the exclusion period for adjacent block harvesting; (3) selecting maximum and minimum opening sizes; (4) selecting priority rules for selecting stands to block and harvest; (5) selecting of block shape control, and (6) selecting convergent accuracy to control evenness of harvest flow.

Planning horizon and period length

Planning horizon is the total time spanned by the plan in years. The planning horizon is often divided into a number of sub periods of fixed length, period length. In the G-SOM, planning horizon must be an integer multiple of period length.

Exclusion period for adjacent block harvesting

Harvesting of adjacent stands is controlled by an exclusion or green up period. Adjacency means that a stand shares a common border with a neighboring stand or stands. In Figure 1, for example, the stands labeled 1 are adjacent with the stands labeled 2. Whether or not a stand can be blocked and harvested is restricted by whether an adjacent stand has been harvested within a specified time period. This restriction is designed to protect wildlife habitat, water quality, or scenic resources (Roise 1990).

Exclusion period (or green up) is defined as the desirable minimum age difference between adjacent stands. For example, in Figure 1, only stands labeled 1 or stands labeled 2 can be harvested during a single exclusion period. The exclusion period can be different for different stands. Non adjacency / exclusion periods have major timing effects on the scheduling of adjacent stands for harvest within a planning horizon.

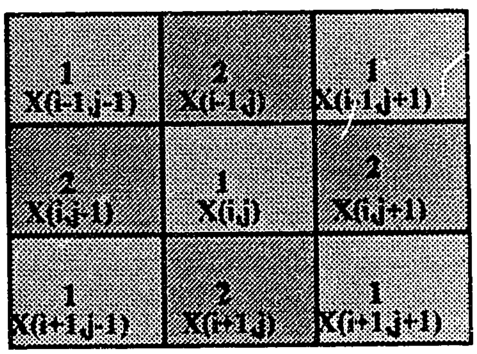


Figure 1. Clearcutting with non-adjacency

G-SOM uses exclusion period as one of important constraints to determine whether a stand can be blocked and harvested.

Maximum and minimum open sizes

Maximum opening size (or maximum cut block size) is a factor for environmental, ecological, economic and public considerations. Larger blocks tend to have smaller per unit logging cost, but also tend to produce more adverse effects on soil erosion, watershed flows, visual amenities and some wildlife (Hunter 1993 and Cumming and Beange 1993). Maximum opening size is an uncertain factor because it is restricted by the forest policy, geomorphologic factor, and forest managers' knowledge. Each forest owner may have different options for maximum opening size. For example, the maximum opening size is 125 hectares in New Brunswick (Baskent and Jordan 1991). In Alberta, the maximum opening size for pine and hardwood types is 60 hectares (Brace, *et al.* 1990) and for spruce types it is 32 hectares.

Small blocks tend to have larger per unit logging cost, but also tend to have less adverse effects on soil erosion, watershed flows, visual amenities and some wildlife. Minimum opening size is designed due to economic consideration. This factor may be determined by the cost analysis for timber harvesting.

The choice of both maximum and minimum opening sizes also affects how harvest blocks are distributed over a forest (Jamnick and Walters 1993). G-SOM uses maximum and minimum opening sizes to control the sizes of cut blocks.

Priority rule for selecting stands to block and harvest

The priority rule for selecting stands to block and harvest is used to determine which stands to concurrently block and harvest (see the section 4.2.2 and the section 4.4.2). There are a number of choices for priority rules in forest industries. For example, stands with oldest tree age are often a priority to be harvested (named as oldest age first). The minimum cut ages (current and regenerated minimum cut ages) provide a control on harvesting merchantable timber in the priority rule of oldest age first. G-SOM uses the oldest age first as the priority rule to block and harvest a real forest.

As an additional blocking rule, G-SOM also provides two options: original site classification or an aggregated site classification. Usually, stands in a forest data base have a site class associated with them. G-SOM can use these existing site classes or it can aggregate site classes by joining adjacent site types into new aggregated site class groups.

Block shape control

G-SOM offers two types of block shape controls: natural stand shapes and approximated square shape. The option for natural stand shapes is to build blocks by following shapes of original stands. Blocks of approximated square are achieved by using a given search length. G-SOM uses square root of maximum opening size ($\sqrt{(\text{maximum opening size})}$) to determine the search length.

Convergent accuracy to control evenness of harvest flow

Convergent accuracy is a relative accuracy of approximating evenflow harvest and controlling the process of solution. Evenflow harvest can be defined as "stable" rate of timber harvest per period over a planning horizon of many periods. The stable rate here is often given within an interval with a relative accuracy named as convergent accuracy (see Figure 2). Evenflow harvest is a constraint of sustaining renewable resource use and maintaining and protecting biodiversity in long term planning. In Canada, a variety of initiatives related to sustained forests are being developed (Griss 1993).

G-SOM uses convergent accuracy to achieve evenflow harvest presented as evenflow annual allowable cut (EAAC) or evenflow period allowable cut (EPAC) and to control the convergence of solution. The smaller the convergent accuracy the more "even" the simulated harvest, but the smaller the convergent accuracy the longer it takes to get a solution.

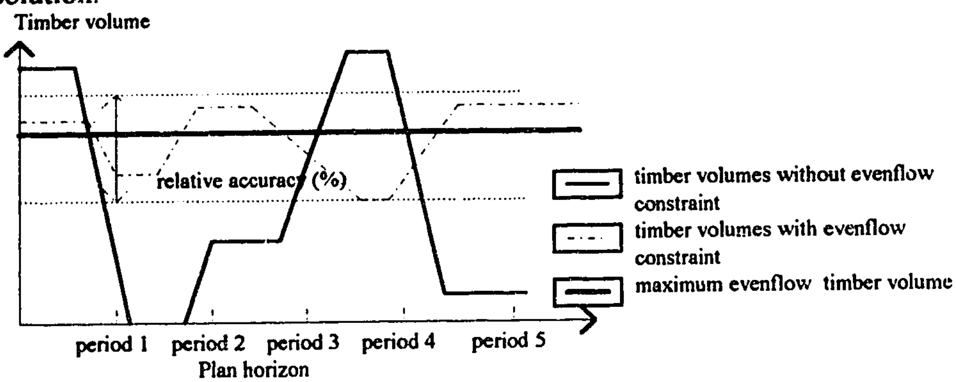


Figure 2. The difference between timber harvest volumes with evenflow and no evenflow constraints

2.4 Spatial Estimation of Timber Supply

Timber supply is spatially estimated by using yield prediction equations (or yield tables) and existing forest data (as mentioned at the section 2.1). Yield models reflect different silvicultural practices, modeling philosophies, and levels of mathematical complexity (Clutter *et al.* 1983 and Duerr *et al.* 1979). The existing forest is built into cut blocks based on site class, species composition, tree age, management intensity (see the section 2.2), and policy constraints (see the section 2.3) and concurrently, these blocks are harvested. In the G-SOM, timber supply is calculated by using the cells and their age within the cut block area and existing or regenerated yield tables based on site class and species. This process is implemented by using grid-based data.

2.5 Maximum Timber Supply and Spatial Harvest Schedule

G-SOM estimates not only a maximum timber supply but also a spatially explicit harvest schedule for the whole planning horizon. The spatial harvest schedule is a time table for timber harvest connected with the spatial location of cut blocks. If data is of sufficient accuracy, this schedule is much more practical than non spatial (traditional) harvest schedules because it can be directly connected with logging operation plans.

3

Model Development

3.1 G-SOM

G-SOM is a model that concurrently dynamically blocks and harvests a forest land base over a planning horizon to maximize annual allowable cut (AAC) or period allowable cut (PAC), subject to constraints of management intensity (see the section 2.2) and policy (detailed in the section 2.3). For example, the major constraints include maximum opening size, minimum opening size, evenflow harvest, non adjacency / exclusion period, and a priority rule for selecting stands to block and harvest for a planning horizon. The planning horizon consists of many sub periods of equal length such as one, five or ten years. Input of the model is in a grid-based data format that represents a real forest. Outputs of the model include maximum evenflow timber volume and spatial harvest schedule for the periods of the planning horizon.

This model automatically formulates all blocking, harvesting, and growth concerns within spatial and non spatial constraints using input modules without regarding the user to develop equations to represent these (detailed in the section 4.4). The harvest blocks within each period of a planning horizon are dynamically built by using the priority rule, maximum and minimum cut block (or opening) sizes, site class, species compositions and age classes. Concurrently, these blocks are harvested if the constraint of non adjacency / exclusion period is satisfied. Each cut block consists of a number of grid-based cells. The cell size depends on the accuracy of the grid data used to represent a real forest.

Obviously, this model process is dynamic. The shapes and sizes of the blocks may change over time. The block shapes can be controlled by selecting approximated square or natural stand shapes (detailed at the section 4.4.2). Blocks may be harvested two or more times depending on the length of a planning horizon and the exclusion period length. The whole process is controlled by maximizing evenflow timber supply.

3.2 Formula

A general expression of G-SOM can be described as follows:

$$\text{Max} \quad PAC_1 = f\,(BS, NA\_EP, BCAGE, PH, PL, PR, RL, SC, SI, SCC, BSC, CA)$$

Subject to

Maximum and minimum opening sizes

$$BS \quad \leq MAX\_OS; \qquad (1)$$

$$BS \quad \geq MIN\_OS; \qquad (1)'$$

Non adjacency and exclusion period

$$NA\_EP = \{\, EP_{ij} \,\}_{N \cdot M} \geq \{LBEP_{ij}\}_{N \cdot M}; \qquad (2)$$

Minimum cut ages

$$BCAGE \quad = \{\{CBCA_{ij}\}_{N \cdot M}, \{RBCA_{ij}\}_{N \cdot M}\} \geq \{\{CMBCA_{ij}\}_{N \cdot M}, \{RMBCA_{ij}\}_{N \cdot M}\}; \qquad (3)$$

Evenflow harvest

$$|PAC_K - PAC_1| \leq CA * PAC_K \qquad k=1, 2, 3, \ldots, PH/PL; \qquad (4)$$

Planning horizon and period length

$$PH \quad \in \{\text{integer multiply of period lengths}\}; \qquad (5)$$

$$PL \quad \in \{\text{integer multipliers of planning horizon}\}; \qquad (6)$$

Priority rule

PR = oldest age first; (7)

Regeneration lag

$RL = \{RL_{ij}\}_{N*M};$ (8)

Site classification

$SC \in \{0,1\};$ (9)

Site improvement

$SI = \{SI_{ij}\}_{N*M}$ (10)

Species composition control

$SCC = \{SCC_{ij}\}_{N*M};$ (11)

Block shape control

$BSC \in \{0,1\};$ (12)

Convergent accuracy

$CA \geq 0;$ and (13)

$CA \leq 1;$ (13)'

Where:

f -- A function of the variables including BS, NA_EP, MAC, PH, PDL, PR, RL, SC, SI, SCC, BSC and CA;

PH -- Planning horizon limited to integer multiple of period length which does not have any upper level limit;

PL -- Period length limited to integer multiplier of planning horizon;

PAC_K -- Period allowable cut at the kth period of a planning horizon, k=1, 2, ..., PH/PL;

BS -- Block size;

MAX_OS -- Maximum opening size;

MIN_OS -- Minimum opening size;

N -- Number of site classes in a forest, which is limited to less than 20 in G-SOM;

M -- Number of species in a forest, which is limited to less than 50 in G-SOM;

NA_EP -- Non adjacency and exclusion period;

EP_{ij} -- Exclusion period length (years) of stands of the ith of site classes and the jth species;

$LBEP_{ij}$ -- Lower boundary for EP_{ij};

BCAGE -- Blocked and cut age in harvest;

$CBCA_{ij}$ -- Currently blocked and cut age for the ith site class and the jth species;

$RBCA_{ij}$ -- Regenerated blocked and cut age for the ith site class and the jth species;

$CMBCA_{ij}$ -- Currently minimum blocked and cut age for $CBCA_{ij}$;

$RMBCA_{ij}$ -- Regenerated minimum blocked and cut age for $RBCA_{ij}$;

PR -- Priority rule for selecting stands to block and harvest;

RL -- Regeneration lag;

RL_{ij} -- Regeneration lag (years) for stands of the ith site class and the jth species;

SC -- Site classification. Option 0 means using reclassification and option 1 means keeping original classification;

SI -- Site improvement;

SI_{ij} -- represents a new site class on stands of the ith site class and the jth species. For example, $\{SI_{ij}\} = \begin{vmatrix} 1 & 1 & 1 \ldots & 1 & 1 \ldots & 1 \\ \ldots & & & & & \\ i & i & i \ldots & i+1 & i \ldots & i \\ \ldots & & & & & \\ M & M & M \ldots & M & M \ldots & M \end{vmatrix}_{N*M}$ with rows indexed by i and columns by j (14)

site class i on stands of the ith site class and the jth species is improved to site class i+1 by using site improvement;

SCC -- Species composition control;

SCC_{ij} -- Represents a new species on stands of the ith site class and the jth species.

For example, $\{ SCC_{ij} \}_{N*M} = \begin{vmatrix} 1\ 2\ 3 \ldots j & j+1 \ldots & M \\ \ldots & & \\ 1\ 2\ 3 \ldots j+1 & j+1 \ldots & M \\ \ldots & & \\ 1\ 2\ 3 \ldots j & j+1 \ldots & M \end{vmatrix}_{N*M}$ with rows indexed by i and columns by j (15)

species j on stands of the ith site class and the jth species is replaced by species j+1 by using species composition control;

BSC -- Block shape control. Option 0 means keeping block shape of natural stands and option 1 is to build block shape approximating square;

CA -- Converagent accuracy which is a relative accuracy (see Figure 2);

4
Algorithm

This paper presents a grid-based search technique with the *0.618* method (Mital 1983) to achieve an optimal solution for the spatial model.

4.1 Assumptions for Algorithm

The following are some assumptions in the G-SOM which can be relaxed later by the further development.

Possible silviculture

Clearcutting and one cut shelterwood (understory protection) methods are two possible harvesting systems to reproduce even-aged stands. Clearcutting describes a spectrum of harvest types in which all of the merchantable stems are removed from some area of forest (Freedman 1991). In Canada, clearcutting accounts for 90 % of all harvesting (Kuhnke 1989). Since many stands often have a developed type of understory, one cut shelterwood or understory protection harvesting is also economically desirable to save on regeneration costs.

The G-SOM algorithm is developed to handle either clearcutting or one cut shelterwood harvesting. Many regeneration options can be simulated using the regeneration lag, site conversion and species selection modules of the algorithm.

Road access

Road access is one of the important components for timber supply analysis. In this study, it is assumed that all the stands are accessible and can be harvested. There are two methods to later relax this assumption: one is to classify the forest by zones that are available sequentially over time for harvest scheduling based on the expected road building schedule; and another is to rebuild the current G-SOM to use road cost as a priority rule.

4.2 Framework for Algorithm

Figure 3 is a framework for the algorithm of G-SOM. It consists of the five modules: (1) grid data generation and input; (2) blocking and harvesting stands; (3) inventory data update; (4) optimizing evenflow timber supply; and (5) outputs. The detailed for each module is referred to in Appendix A.

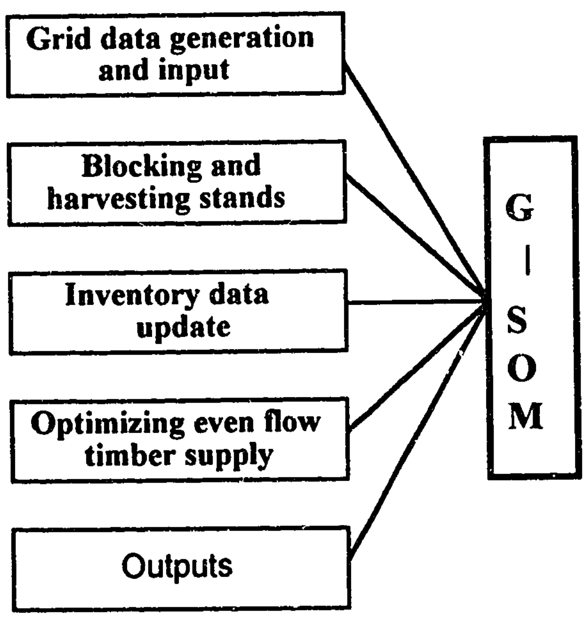


Figure 3. The components of the G-SOM

4.2.1 Grid Data Generation and Input

Grid data can be generated from existing forest data in a coverage. Three layers of grid data, age classes, site classes, and tree species, need to be created and input to G-SOM. A detailed discussion for grid data conversion and sources is given in the section 4.3. The G-SOM model also needs yield tables for the current status and regeneration in order to simulate change over time of the forest.

4.2.2 Blocking and Harvesting Stands

This step will carry out two actions: building of cut blocks and harvest of them. This process is based on a group of multiple control conditions that include the priority rule for selecting harvest stands, non adjacency / exclusion period, maximum and minimum cut block sizes, age classes, species types, and site classes (see the section 4.4 for detail).

4.2.3 Inventory Data Update

As blocked stands are harvested, the inventory related to the regenerated stands in the blocks will be updated over time using regenerated yield tables and regeneration lags. The yield table used is controlled by management decisions regarding site improvement and species selection.

4.2.4 Optimizing Evenflow Timber Supply

Once the harvest stands are blocked and harvested, the harvest timber volumes can be estimated using current yield tables or the regenerated yield tables. G-SOM by iteration, using the 0.618 method determines a maximum evenflow harvest within the accuracy set by the convergent accuracy variable

4.2.5 Outputs

There are two major results produced by G-SOM: (a) a general report (in tables) and (b) a spatial harvest schedule (in maps). The general report includes the input information (see the section 4.6), maximum evenflow harvest, and timber production capacity of different species per period of a planning horizon. The maps of a timber supply plan are output, which include the updated site types and species composition, and the timber harvest schedule with the cutblock distributions per period over the planning horizon.

4.3 Grid Data Conversion and Sources

Grid data are made up of square cells arranged in Cartesian matrix consisting of rows and columns. Grid-based systems divide a forest into discrete uniform cells. Each cell only involves its dominant attribute such as one site class, even-aged tree age, or tree species. Figure 4, for example, shows a grid data structure as a representation of a forest area:

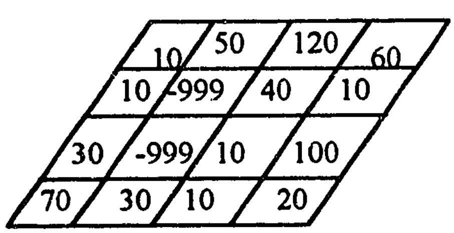


Figure 4. Grid data as a forest area

Where positive numbers 10, 30, 40, ..., 120 represent tree ages and negative numbers -999 represent non timber area that could be lake, road or other non timber types. With the reduction of the cell size, a grid data structure can increase its resolution of representing a real forest. Any inventory map can be transformed into grid data structure. There are two methods that represent forest status in a grid-based data structure. A grid-based data structure can be connected with a database to represent forest status. Figure 5 is a simple example.

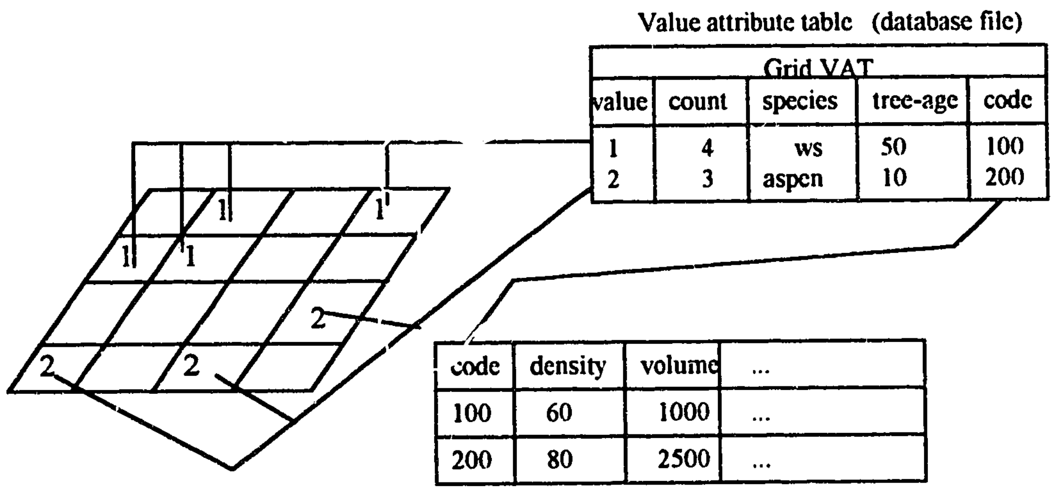


Figure 5 Grid data structure connecting with database (ARC/INFO USERS' QUIDE 1992)

On the other hand, forest status can also be represented by a grid-based data structure with multiple layers. Figure 6 presents an example of this type grid data structure representing forest status. The attributes of each stand in a forest area can be expressed by set notations. In Figure 6, A can be expressed as {a1, a2, a3, ...} (that is, A={a1,a2,a3,...}).

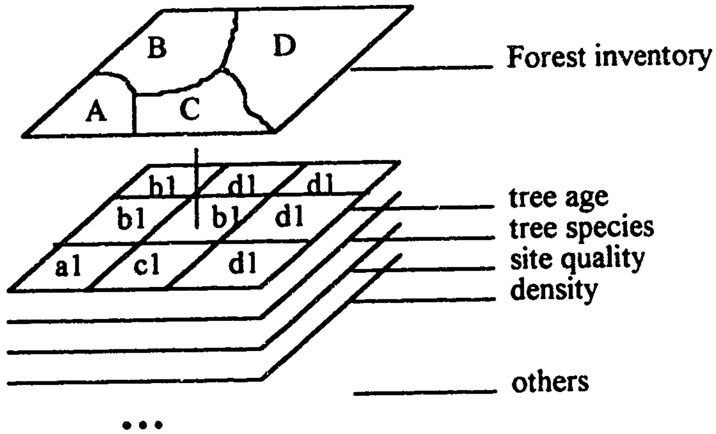


Figure 6. Grid data structure with multiple layers

Grid data can be generated from various sources. The next two sections will describe two common sources, digital vector coverages and files, and raster images.

Vector coverages and files

Vector coverages and files are an important existing source of grid data. In forest management, vector coverages and files, such as ARC/INFO coverages, are often used by government agencies and forest companies. Vector coverages and files can be easily converted into grid data through the vector-to-grid data conversion commands (ARC/INFO USER'S QUIDE 1992).

Raster images

Raster data is another important source for grid data. This potential source is generated from image processing, remote sensing and document scanning. For the generation process, a detailed explanation is given in ARC/INFO USER'S QUIDE (1992).

Using the current GIS and Remote Sensing software packages, we can implement grid data conversion with other source of data.

4.4 Auto Formulating the Model

To include spatial information in the classical LP models requires extensive manual work to formulate the models. In particular, non adjacency formulations are established by a large set of linear equations and extensive, error prone labor time will be spent to create the input data set for a large forest area (Jones, *et al.* 1991). Therefore, to avoid the above disadvantages, an algorithm for auto formulating the model has been developed on the basis of a process including (1) searching for feasible harvest stands, (2) grouping the selected stands (consisting of grid cells) into cut blocks, and (3) optimizing the evenflow timber supply.

4.4.1 Searching for Feasible Harvest Stands

Searching for feasible harvest stands is based on the priority rule for selecting stands with oldest tree age. A practical priority queue with ranked intervals of tree age is used. The queue can be formatted as [age (n-1), age(n)), [age(n-2), age(n-1)), ... [age(m+1), age(m)) where age(n) is some large age bigger than anything in the forest and age(n-1) is some age which includes some of the oldest stands in the forest. Age(n), ... age(m) represent progressively younger stands with age(m) being some overall lower limit age for harvesting any stands in the forest. For any particular species, its minimum possible harvest age as defined by species specific minimum cut ages in the configuration file (see the section 4.6.2) may be older than age(m) in which case the minimum species specific age becomes the effective lower age limit. An example age queue would be [150, 1000), [130,150), [110,130), and [90, 110). Here the search algorithm looks for the oldest stands between ≤ 1000 but > 150 years old in order to start blocking and harvesting. If a stand (grid cell) is found then the grouping part of the algorithm below is engaged. Otherwise, the next search for a stand ≤ 150 but > 130 years old is implemented and the process is continued until stands are found, blocked and cut or the algorithm determines either no stands are available for harvests or a maximum timber supply has been reached. The search starts from initial point (such as (0,0)) to end point (maximum (x, y) coordinates of a grid dataset). The search process will stop when the search has passed through every allocation of grid dataset.

4.4.2 Grouping the Selected Stands into Blocks

After an initial grid cell is found from the oldest first search from above, grouping of other grid cells into a block begins based on non adjacency / exclusion period, age class, site type and species composition. Concurrently, the constraints of maximum opening size, minimum cut block size and block shape control must be satisfied.

The four connected *flood-fill* algorithm is used to search and group the conditioned stands into harvest blocks. The four connected *flood-fill* algorithm is based on the *recursive method* which is simple and powerful (Foley *et al.* 1990). Appendix B contains the developed four connected *flood-fill* algorithm for building cut blocks.

4.4.3 Optimizing Solutions

To achieve an optimal solution, the 0.618 (golden) search method is used and an iterative process with a finite convergence is implemented. The 0.618 search is a classical method that is used to find out an optimal solution (Mital 1983). To implement this method, an initial estimate of harvest is needed. This estimate is generated by multiplying the area of the forest divided by the number of periods times an estimated average yield per hectare which is set currently at 80 cubic meters per hectare. Appendix C contains the program for the algorithm.

4.5 Spatial Data Maintenance and Display

Spatial data maintenance and display involve two parts: maintenance and display for existing inventory, and output and display for plan results. The algorithm has been combined with GIS ARC/INFO. All the data that the model requires can be maintained and managed by using ARC/INFO and the grid data input to the G-SOM can be generated by using the conversion function of ARC/INFO.

To visualize and maintain the distributions of harvesting stands, G-SOM automatically outputs the results for plan into the coverage files. ARC/INFO can be used to display and output these coverage files. For this purpose, both C++ programming and ARC Macro Language (AML) are compiled and generate the automatic output process for G-SOM. Outputs can be displayed as map or table data for a planning horizon (see the 4.2.5).

4.6 Descriptions for Input Data

Three types of input data are required by the G-SOM model and its algorithm: existing forest data; configuration data; and growth data for the existing and regenerated forest. The detailed descriptions for these data are given as follows:

4.6.1 Existing Forest Data

Existing forest data with spatial or geographical features and attributes including tree age, site class, and tree species need to be input to the spatial model. The input data must be in a grid format. The grid data conversion and the generation from coverage files were discussed in the section 4.3.

4.6.2 Configuration

The parameters of the spatial model are input as a configuration data set in an ASCII format. The configuration file reflects the rules for timber supply analysis and plan, silvicultural treatments, and environmental and ecological factors. The components of the configuration file include (1) planning horizon; (2) plan period length; (3) maximum and minimum opening sizes; (4) minimum cut age; (5) cut priority rule; (6) non adjacency / exclusion period; (7) site classification; (8) regeneration lag; (9) site improvement; (10) `species composition control; (11) block shape control; (12) convergent accuracy; and (13) output file controls. The configuration file is named "config.model". Appendix D contains an example of a "config.model".

4.6.3 Growth Data

For growth data, yield tables based on site class, species, and age are used in a 3-D array format. The 3-D array format consists of site class number (site_num) as X Axis, species number (species_num) as Y Axis, and age in number of period (age_num_period) as Z Axis. The period number equals to an integer value obtained by dividing planning horizon length by period length. The input data file is formed as follows:

site_num species_num age_num_period

yield table for site_num=1 and species_num=1

yield table for site_num=1 and species_num=2

:::

yield table site_num=n and species_num=1

yield table site_num=n and species_num=2

:::

yield table site_num=n and species_num=m

Where:

site_num, species_num and age_num_period are not larger than 20, 50, and 50, respectively.

A detailed example is given in APPENDIX E.

5

Sample Study

5.1 Purposes

The grid-based spatial optimization model (G-SOM) and its algorithm have been developed in the chapter 3 and 4. This algorithm has been programmed by C++ and AML (ARC Macro Language) programming languages on the SUN SPARC Station 10. To demonstrate and test the G-SOM, 1993 data for the Cache Percotte Forest in Alberta is used. A spatial analysis and plan for evenflow timber supply is implemented for this area. Maximum evenflow timber supplies are estimated for planning horizons of 20, 50, 100, and 150 years using a period length of 5 years. The spatial pattern of the harvest and the actual value of the harvest in each case are developed subject to constraints of (1) non adjacency / exclusion period (15 years); (2) maximum and minimum cut block sizes (40 ha and 5 ha); (3) priority rule based on oldest age first; and (4) evenflow harvest per period of planning horizons. Finally, sensitivity analysis is used to look at effects of changes in grid cell size and convergent accuracy on allowable cut and computer solution time.

5.2 Data for Sample Area

Figure 7 is an inventory data for Cache Percotte forest. The legend shows the distributions of species on each site class. The number in each stand presents the tree age related to the stand. To solve the problem issued above, the following information is required:

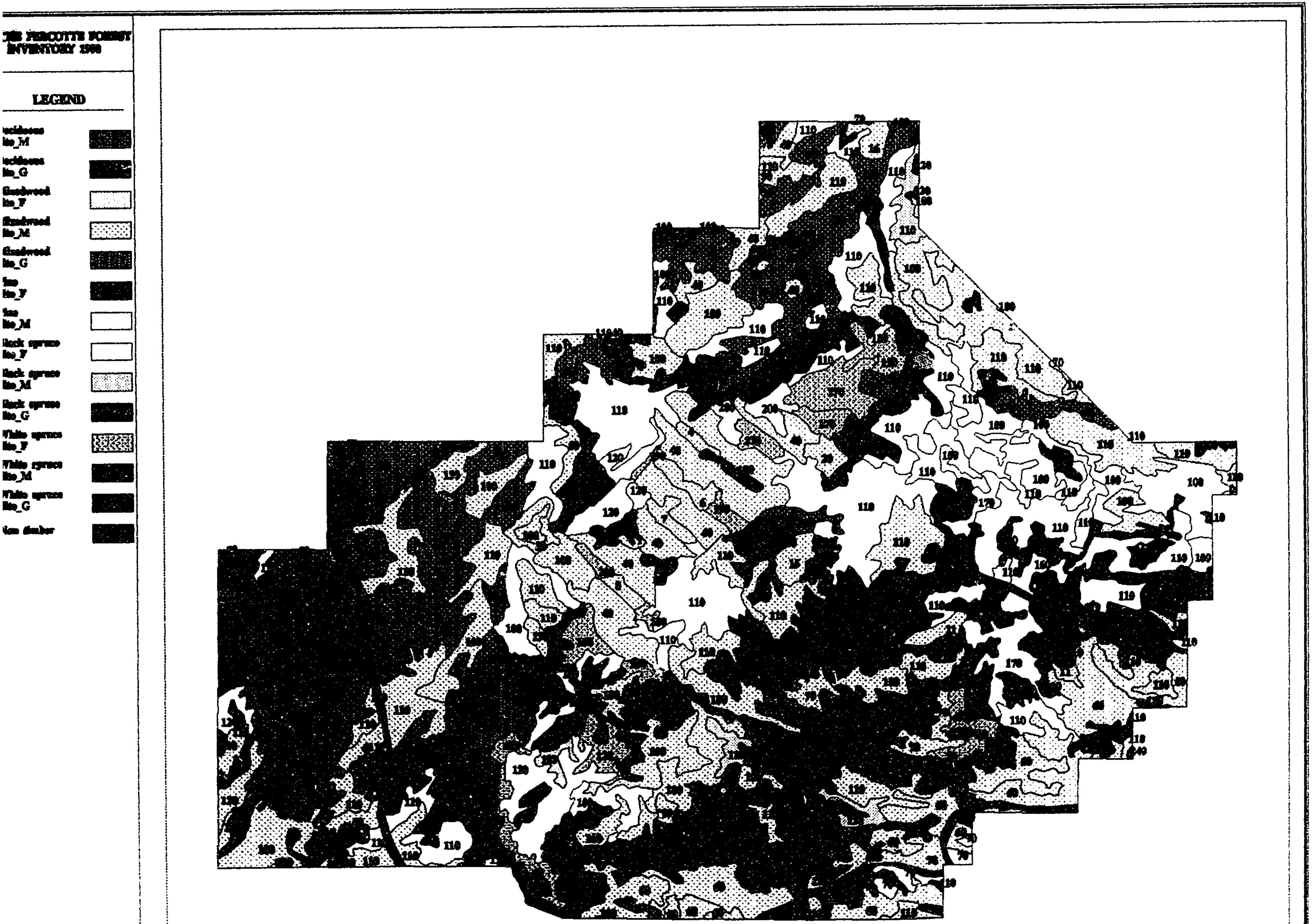


Figure 7.

5.2.1 Site Status

On the basis of the Cache Percotte Forest data base (from Alberta Forest Service), the stand sites have been classified into three types: fair site, medium site and good site. In Figure 8, the fair site, medium site, and good site are respectively of about 10 %, 80 %, and 3 % of the total forest area of 2964 hectares.

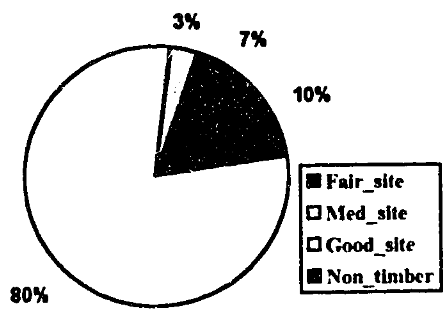


Figure 8. The area distribution by site class in Cache Percotte Forest

5.2.2 Species Composition

This forest area consists of the stands which can be grouped by the species types, deciduous, mixedwood, pine, black spruce, white spruce, and non timber. Figure 7 shows the distributions of both species compositions and site classes.

5.3 Input Data

Input data includes three types of information, grid-based spatial data, configuration data, and current- and regenerated-yield tables.

5.3.1 Grid-based Spatial Data

As described in the section 4.3, the grid data structure with multiple layers is used. Three grid-based files with grid cell size of 10 meters are produced by using the POLYGRID function of ARC/INFO. These three files respectively involve age, site class, and species and are named as f-age10, f-site10, and f-tree10.

5.3.2 Configuration File

The configuration file reflects the planning principles and silvicultural treatments. To create a configuration file in the ASCII format, the following parameters are calculated or assumed.

- Planning horizon (given below):

Four planning horizons, 20 years, 50 years, 100 years, and 150 years are used, respectively.

- Maximum and minimum opening sizes (assumed):

Maximum opening size (hectare)	Minimum opening size (hectare)
40	5

Table 1. Assumed maximum and minimum opening sizes

- Minimum cut ages:

Min_cut_age	Deciduous	Mixedwood	Pine	Black spruce	White spruce
Fair site	70	100	130	160	90
Medium site	55	70	55	100	60
Good site	35	60	40	60	45

Table 2. Minimum cut ages

Minimum cut ages are determined by yield tables and regulation of the minimum cut volume. Here, minimum cut age is calculated based on 50 cubic meters of timber volumes per hectare.

- Cut priority rule (Assumed that the blocks with oldest age are cut first):

[155, 1000], [135, 155), [115, 135), [95, 115), [75, 95), [55, 75), [35, 55)

- Exclusion period (assumed):

The same age, 15 years is assumed for an exclusion period for all site classes and species.

Exclusion period	Deciduous	Mixedwood	Pine	Black spruce	White spruce
Fair site	15	15	15	15	15
Medium site	15	15	15	15	15
Good site	15	15	15	15	15

Table 3. Assumed exclusion period

- Site classification:

If the parameter for site classification is assumed to equal 1, the site classes involve five types of fair site; medium site; fair site & medium site; good site; and medium site & good site. If the parameter is given to be 0, the site classes will be fair site , medium site, and good site (see the section 4.6.2). In this sample study, the parameter is assumed to be 1.

- Regeneration lag (assumed):

Assumed that trees are immediately planted or naturally grow after stands are harvested when a good site preparation and regeneration management are considered. Both site preparation and regeneration are controlled by the table 4. The value 0 means that trees immediately grow after the stands are harvested.

Site preparation	Deciduous	Mixedwood	Pine	Black spruce	White spruce
Fair site	0	0	0	0	0
Medium site	0	0	0	0	0
Good site	0	0	0	0	0

Table 4. Assumed regeneration lag

- Site improvement (assumed):

Site improvement presents site development over time as the site quality is improved (see the section 4.6.2). If 2 is input into the cell with fair site and deciduous, it means that the site quality for stands that are fair site and deciduous is improved from fair class to medium class after stands are harvested. Table 5 presents that site quality is assumed no change in the whole planning horizon.

Site classes	Deciduous	Mixedwood	Pine	Black spruce	White spruce
Fair site	1	1	1	1	1
Medium site	2	2	2	2	2
Good site	3	3	3	3	3

Table 5. Site improvement

- Species composition control (assumed):

If 2 is input into the cell with fair site and deciduous, it means that stands that are fair site and deciduous are changed to mixedwood after these stands are harvested. Table 6 is assumed no species change for each stand following harvest.

Species class	Deciduous	Mixedwood	Pine	Black spruce	White spruce
Fair site	1	2	3	4	5
Medium site	1	2	3	4	5
Good site	1	2	3	4	5

Table 6. Species composition control (assumed)

- Block shape control:

There are two choices for block shape: 0 or 1 (see the section 4.6.2). Here assume that the value 0 is used for all four planning horizons with 20 years, 50 years, 100 years and 150 years.

- Convergent accuracy:

Convergent accuracy is a relative accuracy to control the convergent range for optimal solution. Here a value, 0.005 (0.5 percentage) as a relative accuracy is assumed.

5.3.3 Yield Data

The current yield curves are mainly based on the Alberta provincial full stocked yield tables for 15/10 utilization standard (Alberta Forest Service 1985). The values on the curves reflect the yields at each period (five years). Figure 9 to Figure 13 are produced as five types of yield curves consisting of deciduous, mixedwood, pine, black spruce, and white spruce. For each species, its yield is estimated by using site index, and age data. The future yield curves are based on these same provincial yield functions.

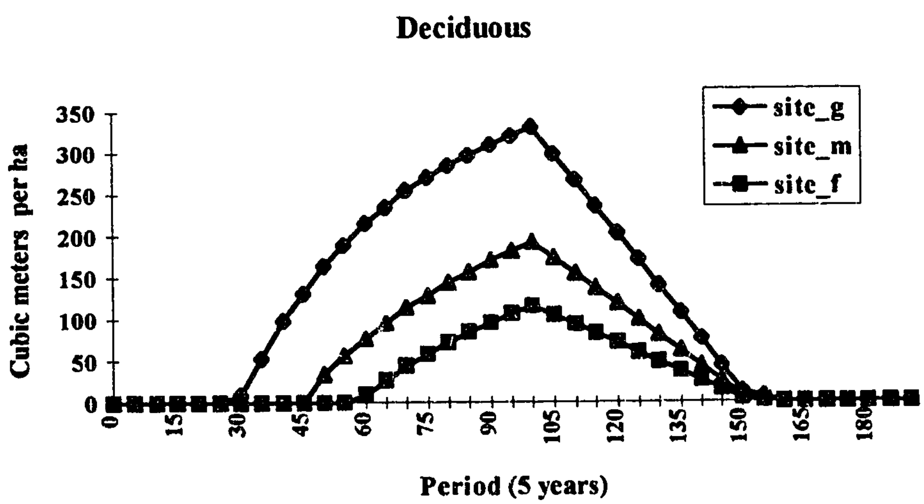


Figure 9. Deciduous yield curves on the different site classes

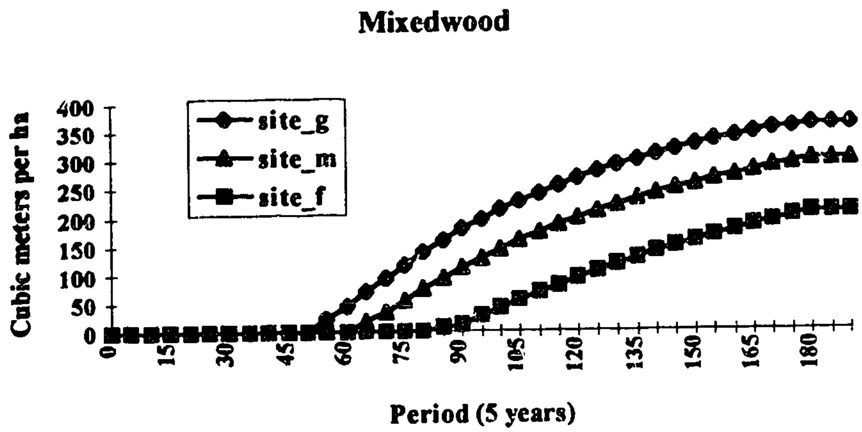


Figure 10. Mixedwood yield curves on the different site classes

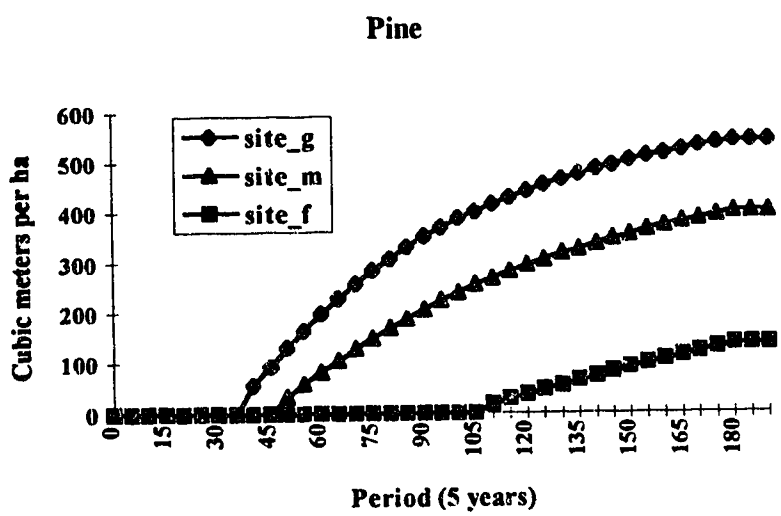


Figure 11. Pine yield curves on the different site classes

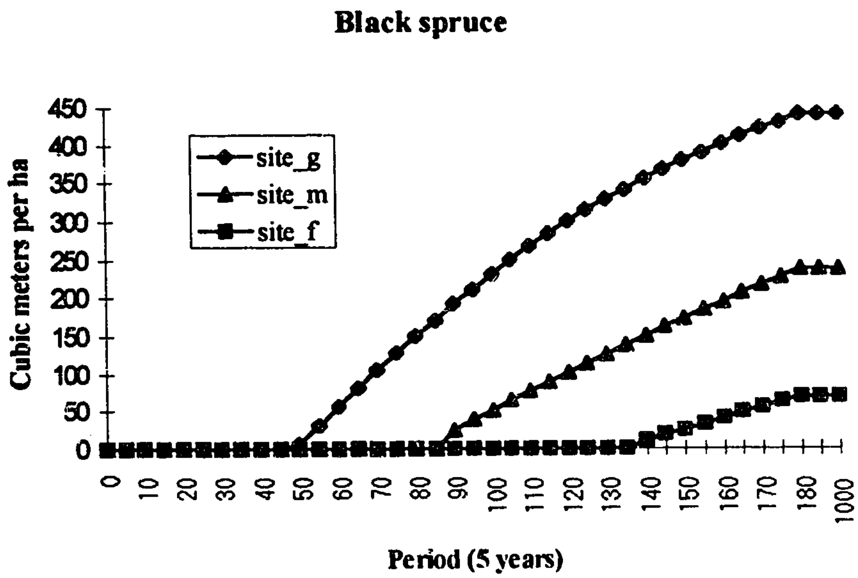


Figure 12. Black spruce yield curves on the different site classes

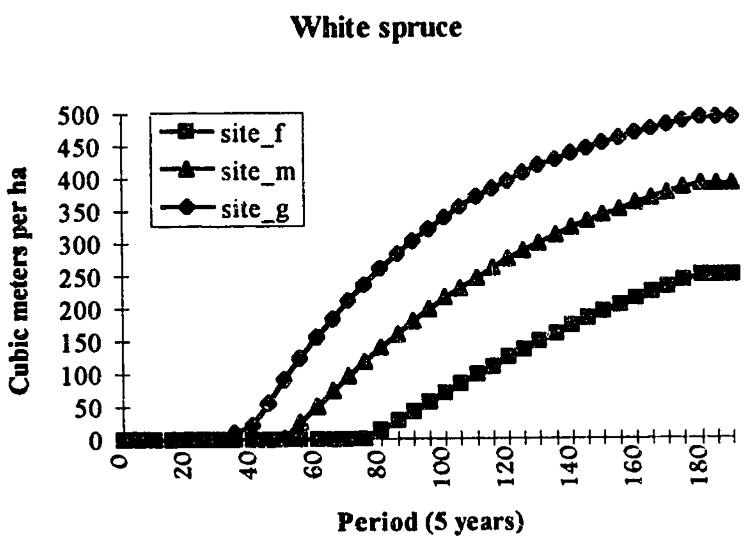


Figure 13. White spruce yield curves on the different site classes

The yield data is created by Figure 9 - Figure 13 , which consists of three site classes, five species and 60 periods. The period length is five years. The data file, yield94.dat is created (see Appendix E).

5.4 Results and Outputs

As the outputs from the spatial optimization model for evenflow timber supply, the following tables and maps respectively display maximum evenflow period allowable cuts and timber supply schedules for 20, 50, 100, and 150 year planning horizons. The site and species dynamics are not displayed because the original site classes and species composition are assumed in the configuration file (see the section 5.3.2).

- 20 year plan

The maximum evenflow period allowable cut is 58004.89 cubic meters per five years in the 20 year plan. Table 7 shows the number of the cut blocks and the harvested area for each period of the planning horizon. The distribution of harvested blocks and their harvesting schedules are displayed in the Figure 14. There are many unharvested stands in Figure 14 caused by the non adjacency / exclusion period. Since no initial period species control is included in the model, Figure 15 only shows the variation of timber supply per species in flow over the 20 year plan. The result shows that the production capacity for deciduous is lower in the first 15 years and then starts to rise. The white spruce has a stable production capacity in this 20 year plan. The timber productions for both pine and mixedwood oscillate. And the black spruce production is low through the whole planning horizon.

Period	Number of cutblocks	Area (hectare)
1993-1998	21	266.30
1999-2003	14	221.83
2004-2008	20	270.85
2009-2013	22	277.73

Table 7. Number of cut blocks and harvested area for each period of 20 year plan

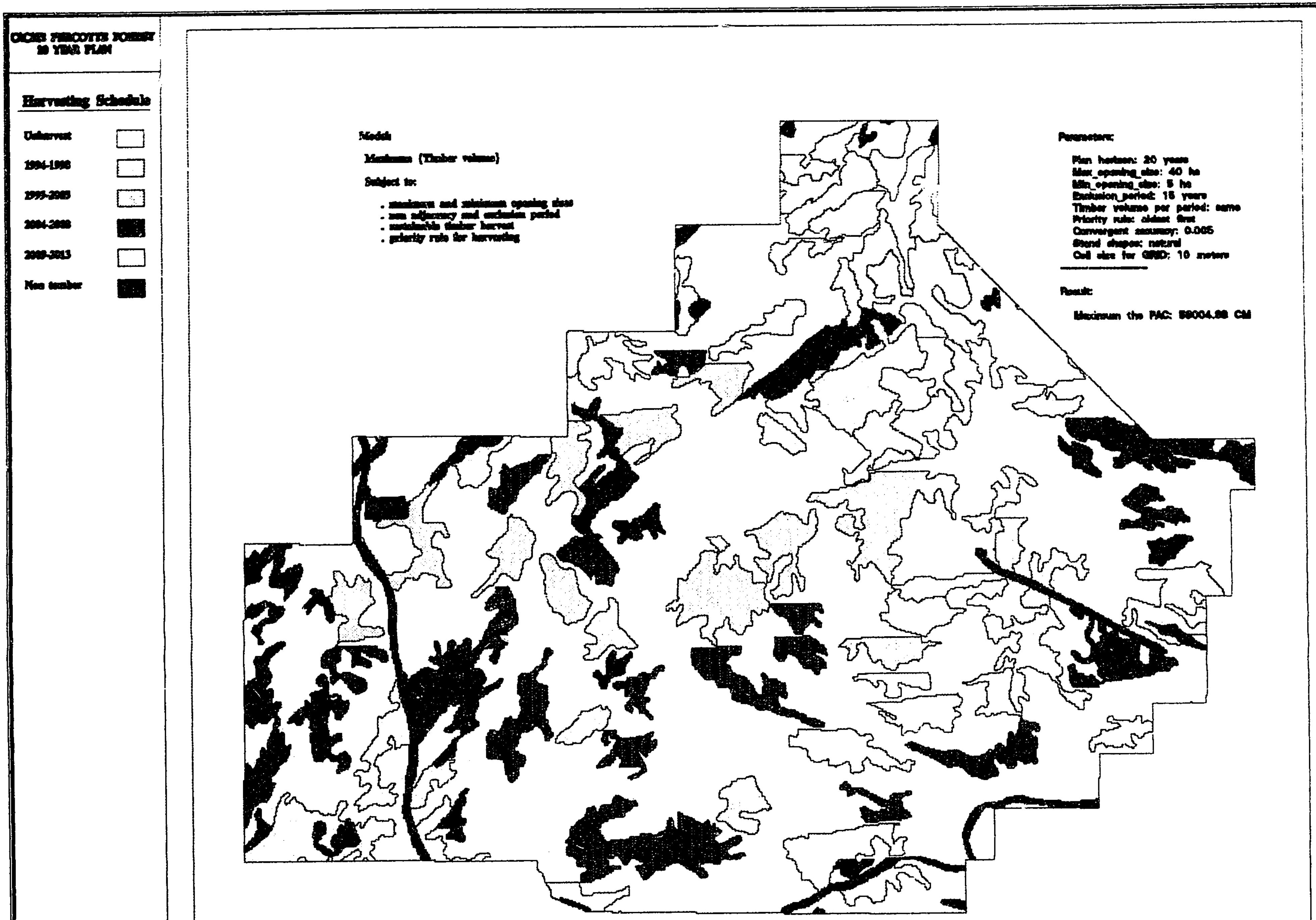

Harvesting Schedule
Unharvest
1994-1998
1999-2003
2004-2008
2009-2013
Non timber
Model:
Maximum (Timber volume)
Subject to:
. maximum and minimum opening sizes
. non adjacency and exclusion period
. sustainable timber harvest
. priority rule for harvesting
Parameters:
Plan horizon: 20 years
Max_opening_size: 40 ha
Min_opening_size: 5 ha
Exclusion_period: 15 years
Timber volume per period: same
Priority rule: oldest first
Convergent accuracy: 0.005
Stand shapes: natural
Cell size for GRID: 10 meters
Result:
Maximum the PAC: 58004.88 CM

Figure 14.

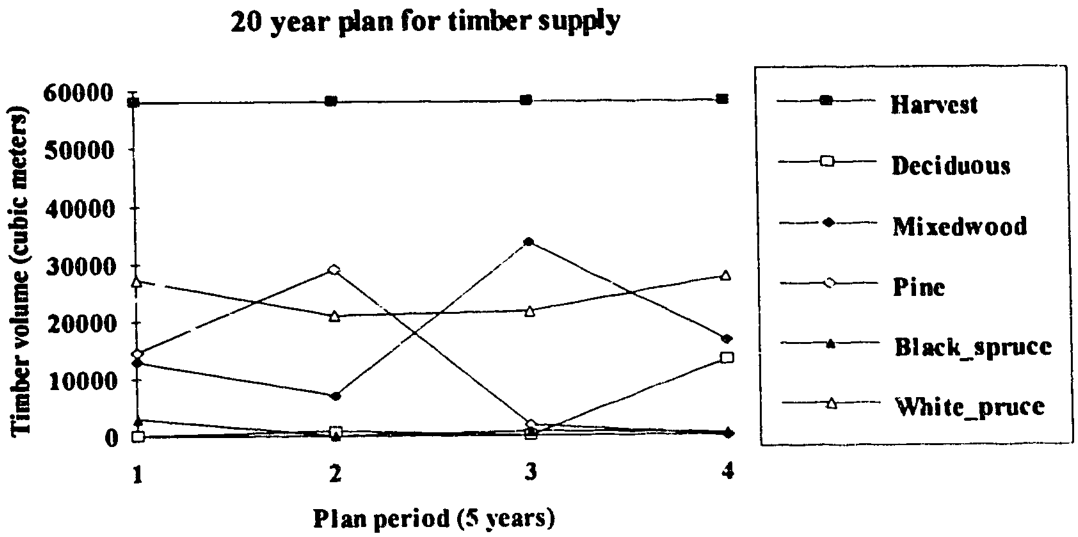


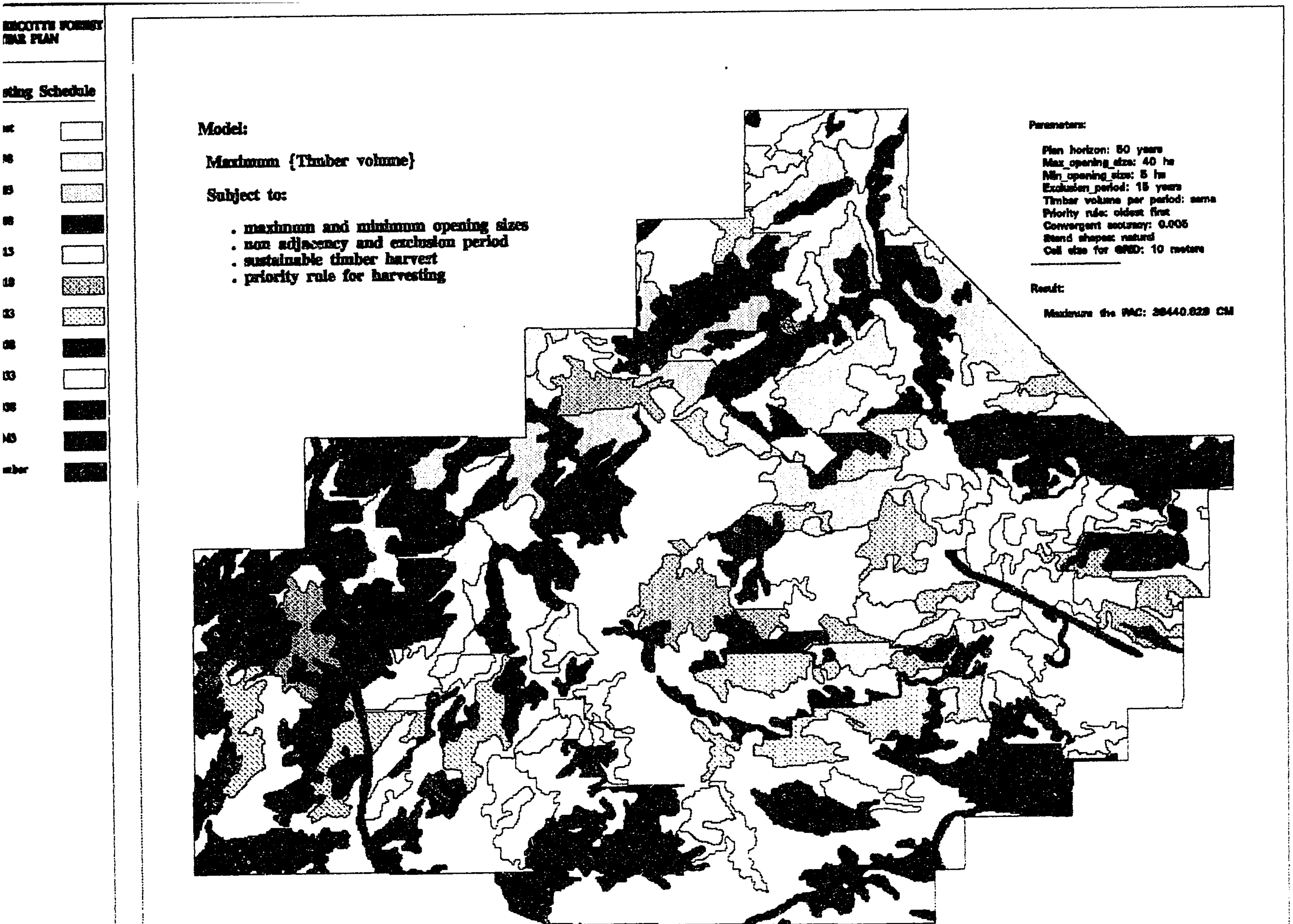
Figure 15. Variation of timber supply per species in each period of 20 year plan

- **50 year plan**

The maximum evenflow period allowable cut is 38440.828 cubic meters per five years in the 50 year plan. Table 8 shows the number of cut blocks and the harvested area for each period in this planning horizon. The distribution of harvest blocks and their harvesting schedules are displayed in the Figure 16. Figure 17 shows the variation of timber supply per species over the 50 year plan. Mixedwood has a stable output for timber production during this planning horizon. And all the other species have a large undulating production.

Period	Number of cutblocks	area (ha)	Period	Number of cutblocks	area (ha)
1993-1998	16	181.91	2019-2023	11	164.23
1999-2003	11	152.35	2024-2028	12	182.56
2004-2008	11	152.10	2029-2033	12	161.62
2009-2013	13	171.56	2034-2038	13	202.89
2014-2018	11	147.69	2039-2043	22	229.10

Table 8. Number of cut blocks and harvested area for each period of 50 year plan



sting Schedule
Model:
Maximum {Timber volume}
Subject to:
. maximum and minimum opening sizes
. non adjacency and exclusion period
. sustainable timber harvest
. priority rule for harvesting
Parameters:
Plan horizon: 50 years
Max_opening_size: 40 ha
Min_opening_size: 5 ha
Exclusion_period: 15 years
Timber volume per period: same
Priority rule: oldest first
Convergent accuracy: 0.005
Stand shapes: natural
Cell size for GRID: 10 meters
Result:
Maximum the PAC: 38440.829 CM

Figure 16.

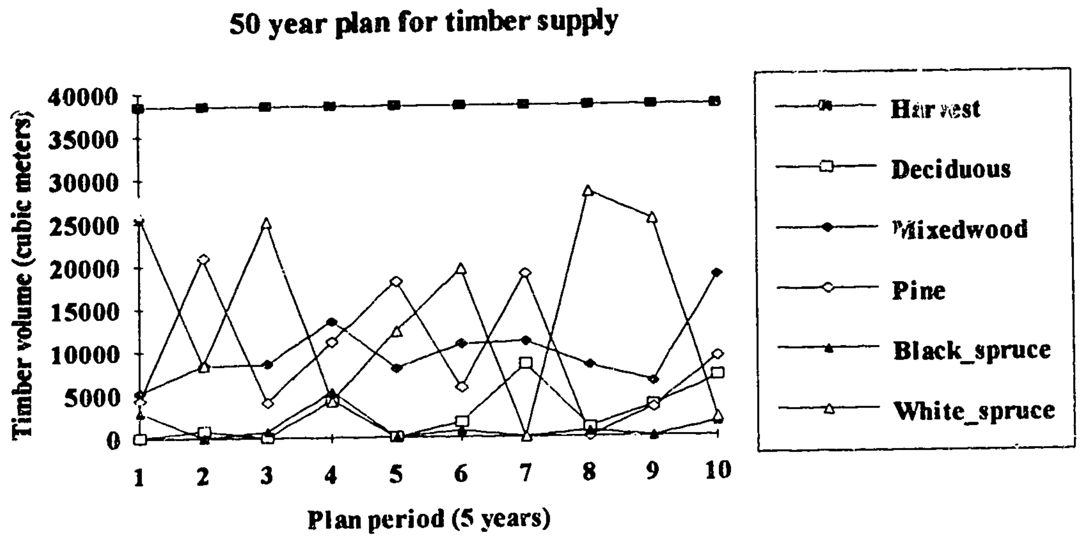
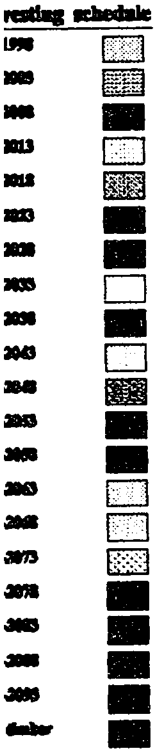


Figure 17. Variation of timber supply per species in each period of 50 year plan

- **100 year plan**

The maximum evenflow period allowable cut is 25937.54 cubic meters per five years in the 100 year plan. Table 9 shows the number of cut blocks and the harvested area for each period within this plan. The distribution of harvest blocks and their harvesting schedules are displayed in the Figure 18. Figure 19 shows the variation of timber supply per species over the 100 year plan. Deciduous has a lower production capacity through the whole planning horizon and all the others present the unstable production capacity.

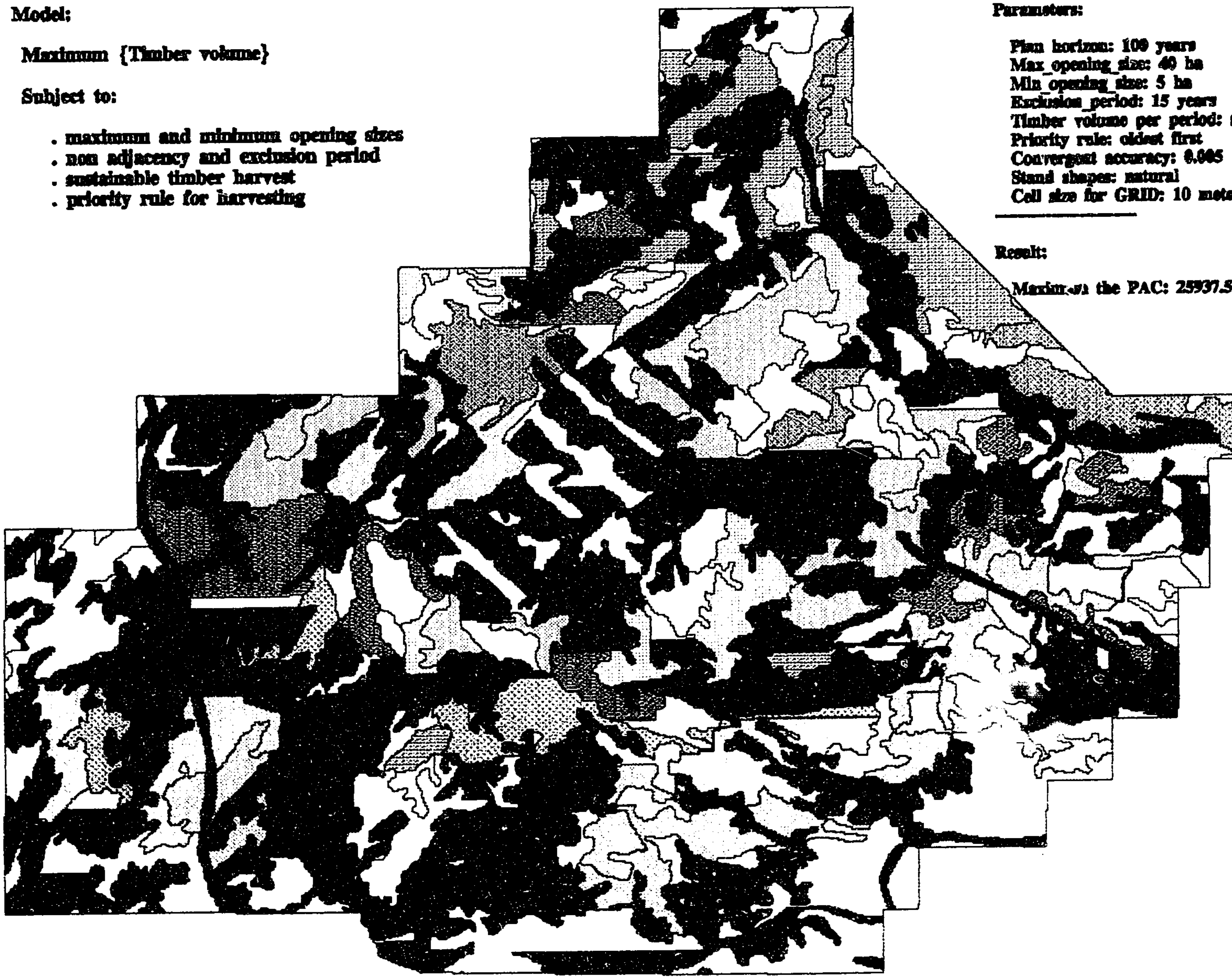


Model:

Maximum {Timber volume}

Subject to:

- maximum and minimum opening sizes
- non adjacency and exclusion period
- sustainable timber harvest
- priority rule for harvesting



Parameters:

Plan horizon: 100 years
Max_opening_size: 40 ha
Min_opening_size: 5 ha
Exclusion_period: 15 years
Timber volume per period: same
Priority rule: oldest first
Convergent accuracy: 0.005
Stand shapes: natural
Cell size for GRID: 10 meters

Result:

[Maximize] the PAC: 25937.54 CM

Figure 18.

Period	Number of cutblocks	area (ha)	Period	Number of cutblocks	area (ha)
1994-1998	10	121.35	2044-2048	11	129.69
1999-2003	10	113.91	2049-2053	7	88.94
2004-2008	7	95.36	2054-2058	6	118.17
2009-2013	8	93.91	2059-2063	9	115.05
2014-2018	5	93.52	2064-2068	6	82.23
2019-2023	7	116.47	2069-2073	4	72.71
2024-2028	11	139.80	2074-2078	12	140.09
2029-2033	11	182.19	2079-2083	12	160.83
2034-2038	7	89.42	2084-2088	7	107.32
2039-2043	12	165.25	2089-2093	6	84.86

Table 9. Number of cutblocks and harvested area for each period of 100 year plan

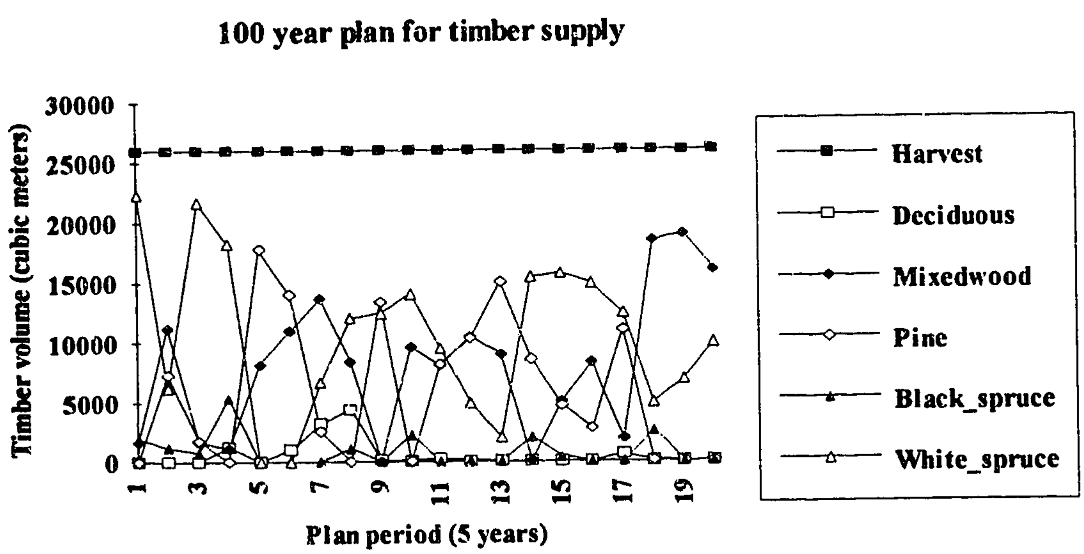


Figure 19. Variation of timber supply per species in each period of 100 year plan

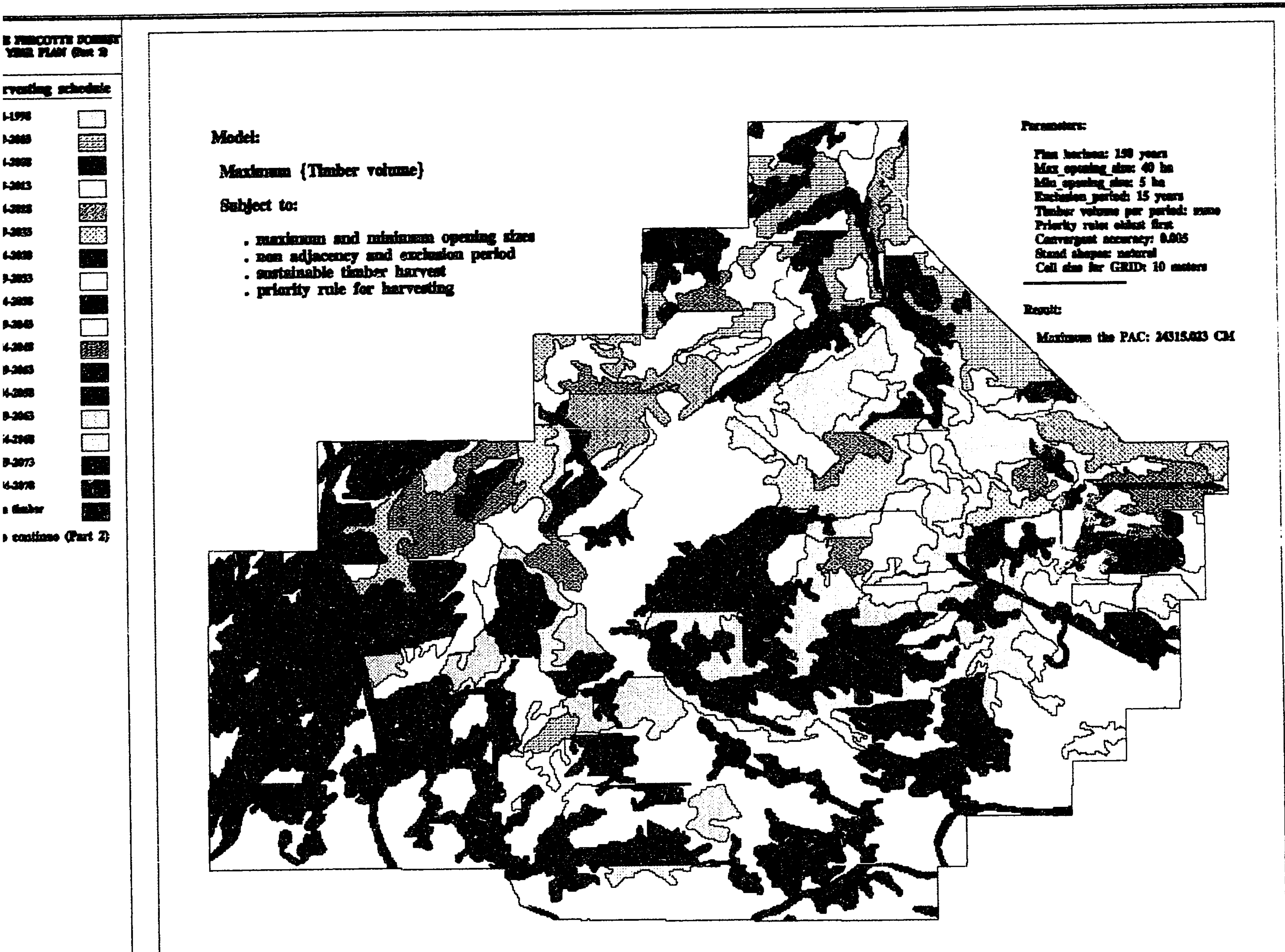
- **150 year plan**

The maximum evenflow period allowable cut is 24315.023 cubic meters per five years in the 150 year plan. Table 10 shows the number of cut blocks and the harvested area for

Period	Number of cutblocks	area (ha)	Period	Number of cutblocks	area (ha)
1994-1998	10	117.64	2069-2073	11	165.47
1999-2003	9	110.15	2074-2078	13	129.32
2004-2008	8	88.34	2079-2083	6	79.65
2009-2013	7	84.96	2084-2088	7	84.96
2014-2018	5	86.10	2089-2093	5	92.05
2019-2023	4	79.31	2094-2098	8	91.18
2024-2028	10	111.50	2099-2103	6	98.61
2029-2033	5	75.06	2104-2108	13	115.10
2034-2038	11	154.44	2109-2113	9	87.74
2039-2043	7	93.95	2114-2118	12	120.09
2044-2048	9	115.87	2119-2123	14	125.67
2049-2053	10	155.82	2124-2128	6	98.53
2054-2058	8	82.78	2129-2133	6	122.75
2059-2063	3	64.16	2134-2138	11	139.42
2064-2068	9	83.62	2039-2143	11	116.66

Table 10. Number of cut blocks and harvested area for each period of 150 year plan

each period within this plan. The distribution of harvest blocks and their harvesting schedules are displayed in the Figure 20 and Figure 21. Figure 22 shows the variation of



Model:
Maximum {Timber volume}
Subject to:
. maximum and minimum opening sizes
. non adjacency and exclusion period
. sustainable timber harvest
. priority rule for harvesting
Parameters:
Plan horizon: 150 years
Max_opening_size: 40 ha
Min_opening_size: 5 ha
Exclusion_period: 15 years
Timber volume per period: same
Priority rule: oldest first
Convergent accuracy: 0.005
Stand shapes: natural
Cell size for GRID: 10 meters
Result:
Maximum the PAC: 24315.033 CM

Figure 20.

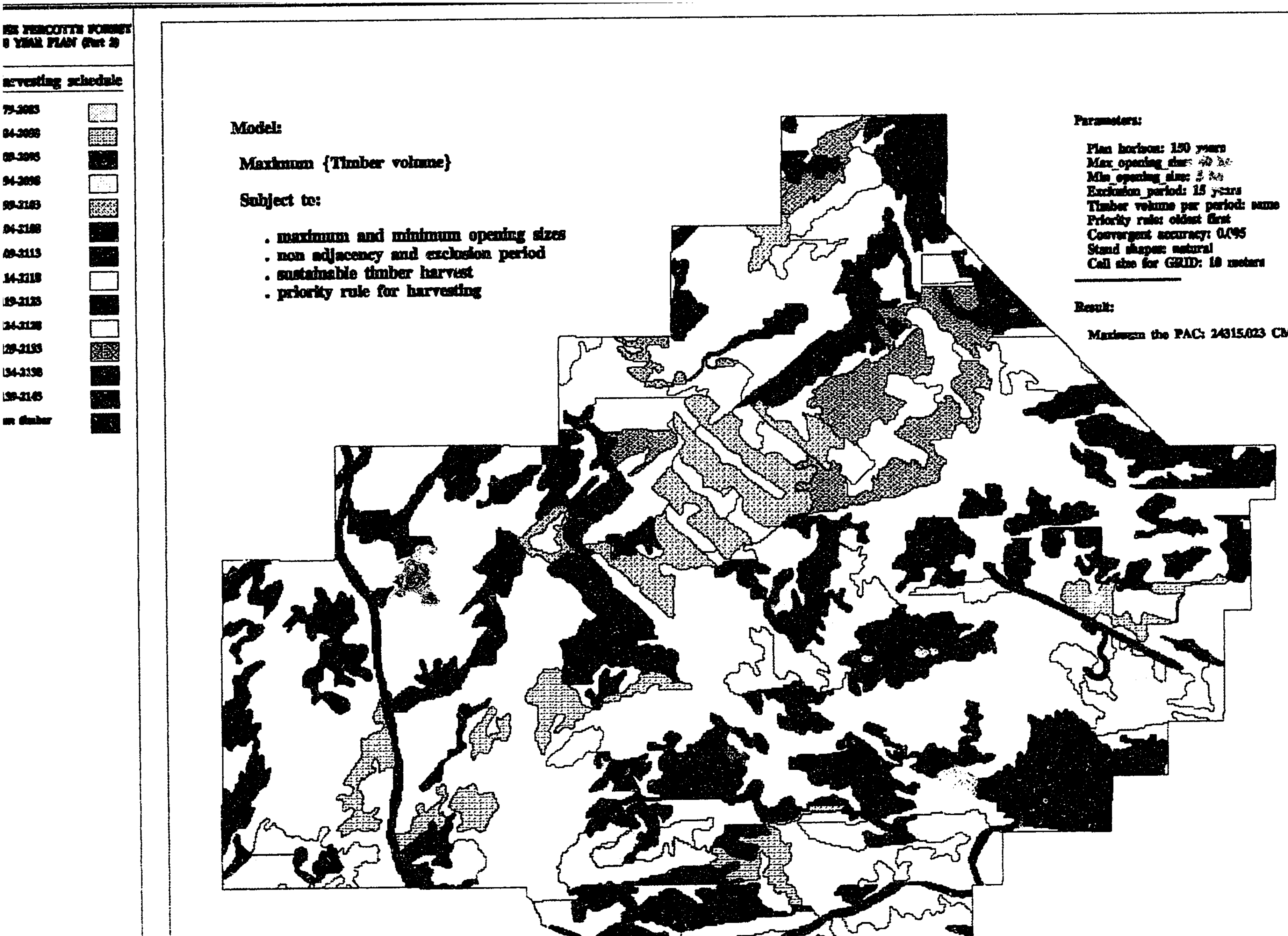

Model:
Maximum {Timber volume}
Subject to:
. maximum and minimum opening sizes
. non adjacency and exclusion period
. sustainable timber harvest
. priority rule for harvesting
Parameters:
Plan horizon: 150 years
Exclusion_period: 15 years
Timber volume per period: same
Priority rule: oldest first
Convergent accuracy: 0.005
Stand shapes: natural
Cell size for GRID: 10 meters
Result:
Maximum the PAC: 24315.023 CM

Figure 21.

timber supply per species over the 150 year plan.

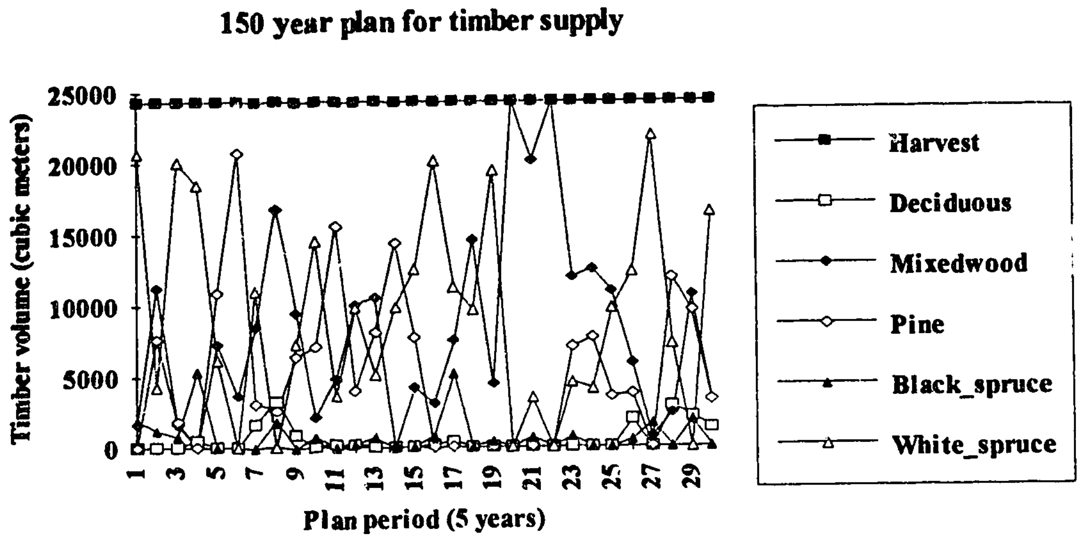


Figure 22. Variation of timber supply per species in each period of 150 year plan

5.5 Sustained Timber Supply

To satisfy the needs and aspiration of next generations of humans, forest industries must develop sustainable capacity of timber productions (Aplet *et al.* 1993 and Pederson 1993). G-SOM provides evenflow timber supply to comply with sustainable timber production. Evenflow timber supply does not mean that the timber supply is sustainable. To achieve a sustained timber supply, as one of applications of G-SOM, maximum evenflow timber supplies for six planning horizons are estimated by individually running the G-SOM for each planning horizon. Table 11 and Figure 23 shows how the evenflow timber volume changes as the planning horizon varies. Evidently, sustained timber supply can be achieved when planning horizon is over one or more rotations.

Planning horizon	20	50	100	150	250	300
Harvest (KCM)	58.004	38.441	25.938	24.315	22.848	22.154

Table 11. The relationship of the maximum evenflow period allowable cut and planning horizon

(KCM -- kilo-cubic meters)

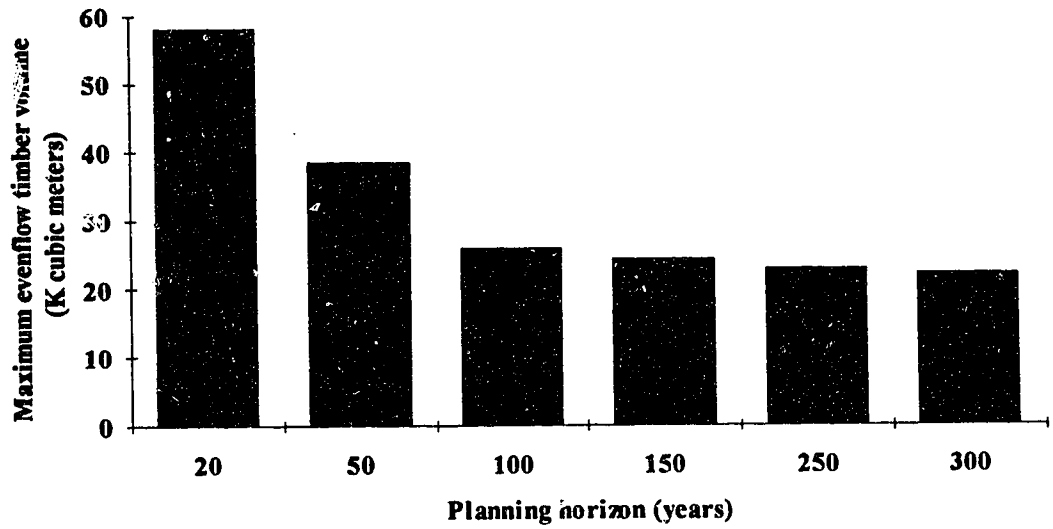


Figure 23. The relationship of the maximum evenflow period allowable cut and planning horizon

5.6 Sensitivity Analysis

Sensitivity analysis is a procedure for dealing with uncertainties. These uncertainties involve grid data conversion from coverage data format, silvicultural decision-making, and so on. This section presents the sensitivity analysis for changes in grid cell size and convergent accuracy. The sensitivity of spatial constraints to results will be discussed in the chapter 6.

5.6.1 Data Conversion

Small grid cell size may increase the solution accuracy but it may also increase requirements for computer systems (Bregt *et al.* 1991). G-SOM only can handle a grid dataset of 2000 (rows) x 2000 (columns) or smaller based on the hardware limitation (SPARC station 10). Table 12 is a result from three types of grid cell sizes, 5 meters, 10 meters and 25 meters. All other parameters for the case study 50 year plan of period length 5 remain the same.

Grid cellsize (meters)	5	10	25
CPU on SUN SPARC Station 10	43.31 minutes	10.20 minutes	2.39 minutes
Storage space (MB)	22 MB	5 MB	1 MB
Maximum PAC (Cubic meters)	40757.37	38440.82	38517.96

Table 12. The sensitivity of grid cellsize to maximum PAC, storage space, and CPU

Table 12 shows that the smaller the grid cell size, the longer the CPU time and the larger the storage space is required. However, maximum period allowable cut does not change regularly because the conversion from coverage file (polygon shapes) to grid file causes the areas associated with certain attributes to be changed irregularly.

5.6.2 Convergent Accuracy

Convergent accuracy is a related accuracy (%) that is used to control the iterative process of G-SOM (see the section 4.4.3). Usually, the higher the accuracy, the longer the spent CPU time and the higher the resolution of the achieved result. Table 13 presents results from various values for convergent accuracy, assuming that the other parameters are the same as those in the previous 50 year plan of period length 5. This demonstrates, at least for a 50 year plan, that the sensitivity of solutions is not great to large changes in CA and that CPU solution times are not greatly ef[illegible]cted.

Convergent accuracy (%)	5	0.5
CPU on SUN SPARC Station 10	8.27 minutes	10.20 minutes
Maximum PAC (Cubic meters)	37944.704	38440.828

Table 13. Sensitivity of convergent accuracy to maximu[illegible]

6
Discussion

The followed discussion is divided into 3 parts:

A. Effects of spatial constraints on the allowable cut;

B. How G-SOM could be used to demonstrate effects of (i) tree species diversity; (ii) alternative silvicultural strategies; (iii) wildlife habitat concerns;

C. Advantages and disadvantages on the G-SOM algorithm.

6.1 Effect of Spatial Constraints on the Allowable Cut

Spatial constraints significantly impact both the distributions of harvest blocks and the allowable cut. For example, maximum and minimum opening sizes, exclusion period and maximum age difference (priority rule) for each cut block have different influences on the allowable cut. To respectively establish the relationship between allowable cut and each spatial constraint, a series of runs was made while changing one spatial constraint. The results of this sensitivity analysis are shown in Table 13.

Maximum opening size (hectare)	40	80	40	40	40	40	40
Minimum cut block (hectare)	5	5	2	10	5	5	5
Exclusion period (years)	15	15	15	15	10	15	15
Age difference in each cut block (years)	20	20	20	20	20	30	20
Cut block shape (0 - natural, 1 - square)	0	0	0	0	0	0	1
PAC for 50 year plan (cubic meters) Relative increment (%)	38441 0%	39702 +3%	41526 +8%	32824 -15%	43114 +12%	38604 +0%	40359 +5%
PAC for 250 year plan (cubic meters) Relative increment (%)	22848 0%	22421 -2%	24620 +8%	12058 -47%	23424 +3%	22784 -0%	18996 -17%

Table 14. Relationships between allowable cut and each spatial constraint.

Table 14 demonstrates the effect of each spatial constraint on a short run 50 year plan which has harvest levels which would not be sustainable in the long term and on a 250 year plan which has harvest levels at or very near sustainable long run levels. Changing minimum cut block size form 5 hectares to 2 hectares or 10 hectares causes large changes in harvest in both the 50 and 250 year plans. As expected, the 2 hectare minimum cut block size increases cut (50 year plan +8% and 250 year plan +8%). Also as expected the 10 hectare minimum cut block size decreases cut (50 year plan -15% and 250 year plan -47%). As expected, a larger minimum cut block size leads to smaller allowable cuts because many small blocks are left unharvested because they are too small yet to different in terms of age, site or species from their neighbors to ever be made into cut blocks. Three changes (larger maximum cut block size, bigger age difference in each cut block, and square versus natural block shape) cause increases in harvest in the 50 year plan while causing decreases in the 250 year plan. The reason for this difference is that in the short run where much of the harvest is made up of existing growing stock volume and relatively less is made up from growth or regrowth after harvest. You can get more volume faster with bigger, more age diverse and squared shape blocks. With longer plans where much of the harvest must come from growth and regrowth (and reharvest) of stands in the forest, you can better capture differences in growth by cutting smaller, less diverse, natural shaped blocks. Reducing the exclusion period from 15 to 10 years caused an increase in harvest in both the 50 and 250 year plans as expected and as expected the effect is bigger (+12%) for the 50 year plan than for the 250 year plan (+3%).

6.2 Application of G-SOM

6.2.1 Modify and Display Tree Species Diversity

The maintenance of tree species diversity is of concern with the current and future evenflow timber supply and silviculture planning. How to manage for this relationship is one of the goals of biodiversity research. The G-SOM not only can predict the future landscape over time but also may provide a tool for biodiversity study.

G-SOM can demonstrate tree species diversity resulting from harvest and with silvicultural strategies over time. Figure 22 shows the timber production capacity for different species over a 150 year planning horizon. To demonstrate how species varies, assume that species composition control in the configuration file (see the section 5.3.2) is changed into the Table 15, which increases stand number and area for pine after first rotation by replacing medium and good site deciduous stands with pine stands.

Species class	Deciduous	Mixedwood	Pine	Black spruce	White spruce
Site fair	1	2	3	4	5
Site medium	3	2	3	4	5
Site good	3	2	3	4	5

Table 15. A new species composition control (assumed)

Figure 24 shows the timber production capacity under a new species composition control for a 150 year planning horizon (compared Table 6 with Table 15). The production of pine increases after 75 years in the 150 year plan, which indicates the species change. Therefore, this method can effectively modify and display species diversity. However, how to directly control capacity of each species per period is beyond this study.

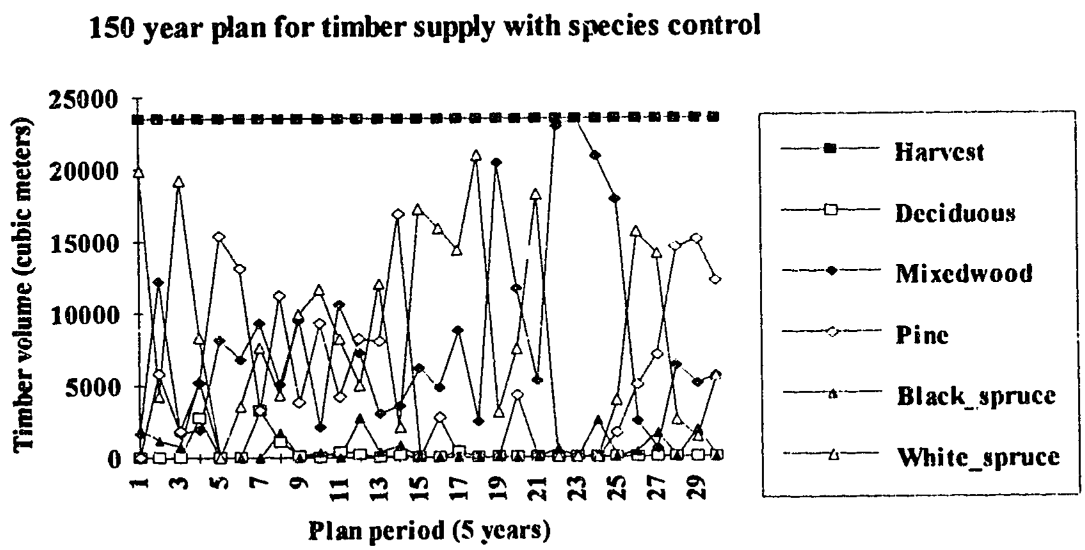


Figure 24. 150 year plan with a new species composition control

6.2.2 Effects of Alternative Silvicultural Strategies

In the G-SOM, silvicultural practice is reflected by the yield tables in combination with regeneration lag, site improvement, and regeneration species control. Using the G-SOM, silvicultural practice could be examined. In particular, for a long-term planning, future inventories could feed back and demonstrate what effects various silvicultural strategies would have on the landscape, timber production, tree species diversity, *etc*. For example, changing regeneration lags of mixedwood, black spruce and white spruce from 0 to 20 years (using one cut shelterwood or understory protection) or from 0 to negative 20 years (delaying 20 years to grow the mixedwood, black spruce and white spruce) (see Table 16) causes large change in harvest in 250 year plan. As expected, the plus 20 year regeneration lag for mixedwood, black spruce and white spruce increases cut (+13.6%) in the 250 year plan. Also as expected the negative 20 year regeneration lags decreases the cut (15.3%) in the 250 year plan.

	regeneration lag (1)	regeneration lag (2)	regeneration lag (3)
Deciduous (years)	0	0	0
Mixedwood (years)	0	+20	-20
Pine (years)	0	0	0
Black spruce (years)	0	+20	-20
White spruce (years)	0	+20	-20
PAC for 250 year plan	22848(cubic meters)	25944 (cubic meters)	19366(cubic meters)
Relative increment	0%	13.6%	-15.3%

Table 16. Effects of regeneration lags on allowable cut

To demonstrate how G-SOM can be used to investigate effects of species conversion on allowable cut in long-term planning, mixedwood is changed to white spruce by using regenerated species control (see Table 17) and a 30 year regeneration lag (one cut shelterwood or understory protection) for white spruce is applied. The allowable cut (25725 cubic meters) in the 250 year plan increases 12.6% compared to the result (22848 cubic meters) from the run with the options of no species changed (see Table 6) and 0 regeneration lag (see Table 4).

Species class	Deciduous	Mixedwood	Pine	Black spruce	White spruce
Site fair	1	5	3	4	5
Site medium	1	5	3	4	5
Site good	1	5	3	4	5

Table 17. Species conversion in long term plan

6.2.3 Wildlife Habitat Concerns

The G-SOM would provide spatially explicitly forest descriptions over time which could be used to analysis spatially depended on wildlife habitat models over time to protect wildlife carrying capacity over time.

6.3 Advantages and Disadvantages of the G-SOM Algorithm

- Auto blocking and harvesting a real forest

Within a set of spatial and non spatial constraints, G-SOM can automatically, concurrently block and harvest a real forest to generate a maximum evenflow and a spatially explicit harvest schedule. The harvesting stands are blocked as closely as possible to effectively decrease logging cost. The shapes of cutblocks can be controlled by designing the search method.

- GIS / G-SOM interface

A GIS is a computer-based system that provides the following four sets of capabilities to handle georeferenced data: (1) input; (2) data management (data storage and retrieval); (3) manipulation and analysis; and (4) output (Aronoff 1993 and Burrough 1986). ARC/INFO as one of very powerful GIS software packages, is applied to the G-SOM to produce and display the spatial data such as age, site class and species. The functions of ARC/INFO are effectively used to automatically create and input the grid-based files for the G-SOM.

Future simulated forests produced by G-SOM are automatically converted into the coverage files that ARC/INFO can be used to display. This is automatically done by a set of C++ programming and AML language routines.

- Little knowledge required

Due to significant automation of the GIS / G-SOM interface and a menu driven process, little knowledge for the spatial model and GIS is required by operators or users. Users only need to input the spatial inventory data in grid-based format, the configuration file by using a simple menu, and the yield table files.

- Grid-base data structure

A grid data structure can efficiently simplify the spatial model formulation by using C++ programming and the 0.618 method speeds up the data processing and the solution optimization.

- Some disadvantages

The grid-based algorithm has some disadvantages in that large forest and small grid sizes will produce very large data sets that may require large computer disk and memory to enable G-SOM to function. Large grid sizes reduce the size of the problem but reduce the accuracy of the representation of the forest spatial data. However, these disadvantages may be overcome with the use of powerful computers. Reducing grid cell size may increase the accuracy if the computer disk space is available.

7
Summary and Conclusion

The grid-based spatial optimization model for evenflow timber supply (the G-SOM) was developed and discussed in the chapter 2 and chapter 3. The algorithm was designed in the chapter 4 and its sample application was studied in the chapter 5. The effect of the spatial constraints on the period allowable cut, the tree species diversity and the advantages and disadvantages were mainly discussed in the chapter 6.

The development of the G-SOM is based on an *integration use of the principles of timber management, GIS, modeling, and computer programming.* The functions and characteristics of the G-SOM can be simply summarized and concluded as follows:

- This G-SOM can provide forest managers a tool to find out where, when, how to harvest a real forest over a planning horizon, subject to the multiple spatial and non spatial constraints.
- The spatial optimization method is different from the existing LP models and simulation models. It can, temporally and spatially, concurrently block and harvest a real forest, optimize an evenflow timber supply and produce its spatial harvest schedule for the planning horizon.
- Because regenerated yield tables are used in this model, alternative choices for silviculture management can be investigated.
- The spatial model also is a tool of biodiversity studies dependent upon temporal and spatial habitat diversity.

- Grid data structure is used and a programming with C++ and AML (GIS ARC/INFO) is developed for the G-SOM.

Using a case study approach with data for Cache Percotte Forest near Hinton Alberta, G-SOM was able to block and harvest this forest to achieve a maximum evenflow harvest subject to spatial and non spatial constraints. Spatial outputs of the forest resulting from the simulated harvesting and growth were produced at various future predicted times.

Additionally using a sensitivity analysis, the effects of changes in various policy controlled spatial concerns (maximum and minimum block sizes, exclusion period, cut block shape and age difference permitted in each cut block). Raising minimum cut block size from 5 ha to 10 ha, reducing exclusion period length from 15 years to 10 years, and changing cut block shape from natural stand shape to approximated square shapes caused significant changes in harvest levels. Whereas changes in maximum block size from 40 to 80 hectares and age diversity permitted in a cut block from 20 to 30 years caused minimal changes in allowable cut. Simulating natural regeneration with a 20 year regeneration lag, simulating understory protection to protect a 20 year old understory and simulating mixedwood conversion to spruce all predicted large effects on allowable cut.

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APPENDIX A: Data flow chart for process of the G-SOM

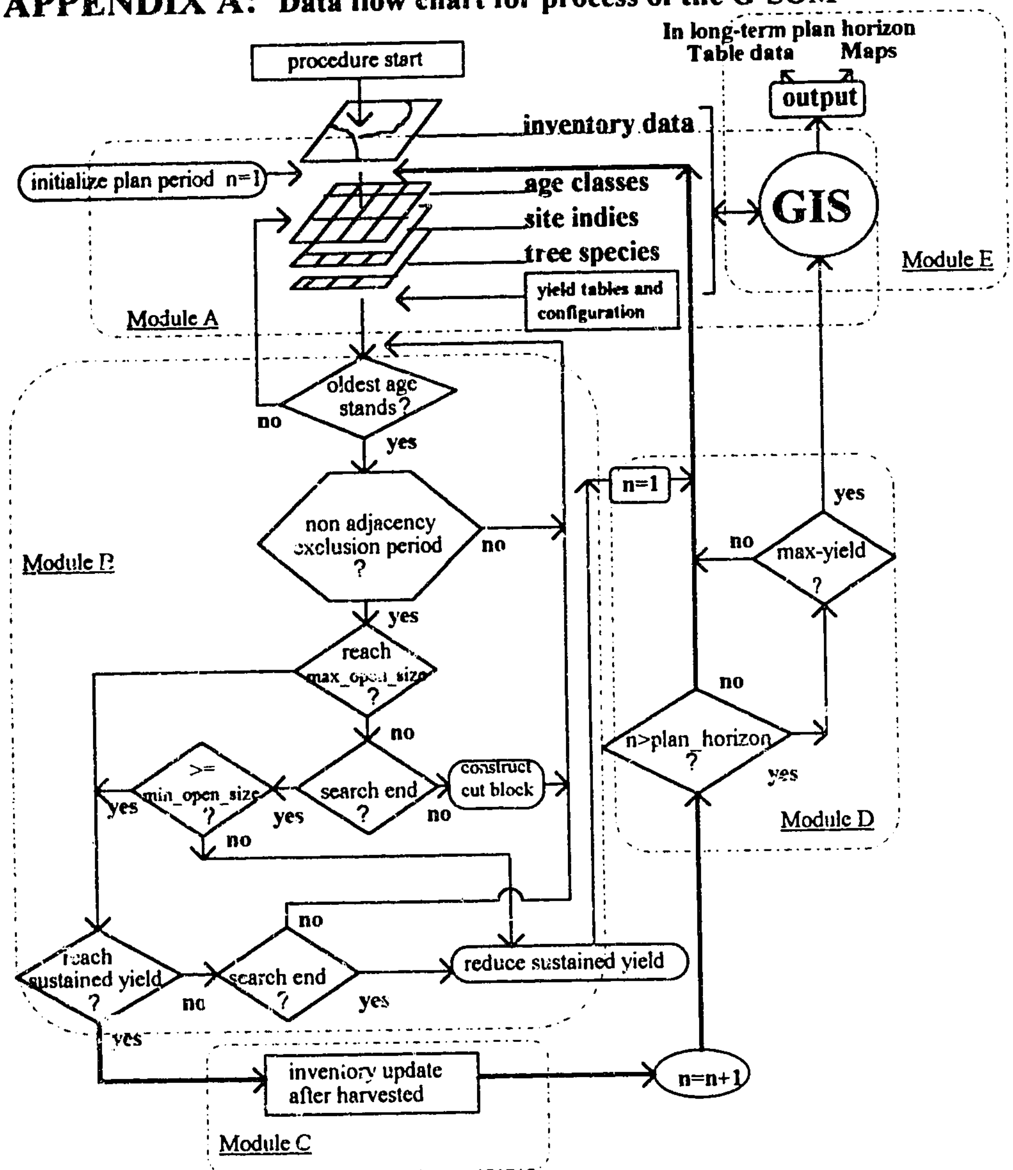

Figure 25. Data flow chart for the model process

Where Module A -- Grid data conversion and input;

Module B -- Blocking and harvesting stands;

Module C -- Inventory data update;

Module D -- Optimizing evenflow timber supply; and

Module E -- Outputs.

APPENDIX B: Four connected *flood-fill* algorithm for building cut blocks

```
Block_build (x, y)
x, y: integer;
begin
        current = getpixel (x, y);
        if ( (site classification: ok) and (maximum opening size: ok) and (tree age : within
the ranked queue age interval) and (species composition : ok) and (non adjacency : ok)
and (the pixel : not searched before))
                {
                  Begin
                        setpixel (x, y);
                        if ( non adjacency: ok)
                                {
                                  Begin
                                        setpixel (x, y, non adjacency : ok; pixel : searched;
                                                opening size : increment);
                                        if (x-1 > = lower boundary)
                                                block_builder (x-1,y);
                                        if (y-1 > = lower boundary)
                                                block_builder (x,y-1);
                                        if (x+1 <= upper boundary)
                                                block_builder (x+1,y);
                                        if (y+1 <= upper boundary)
                                                block_builder (x,y+1);
                                  End;
```

```
            End;
End;
```

Lower boundary and upper boundary are two control parameters that are used to control block shapes.

APPENDIX C: The Algorithm for optimizing solution

Algorithm:

```
max_pac, operation_pac, initial_value : double   { max_pac -- a special variable for
        optimization reference; operation_pac -- a variable expresses timber volumes in a
        period; initial_value -- initial value at starting iterative}
iterative_num : integer   {iterative number }
accuracy : double { relative solution accuracy}
pac_temp : double { temporary variable}

Begin0
    iterative = 0;
    max_pac = initial_value;
    operation_pac = initial_value;
    Begin1
        iterative++;
        for (period = 1; period <= sum of all periods; period ++)
                {
                        calculate pac_temp; /* Caiculating period allowable cut (PAC) */
                        if (operation_pac - pac_temp > accuracy * operation_pac)
                        {
                           max_pac = operation_pac,
                           operation_pac = (1-0.618) * pac_temp + 0.618 * operation_pac;
                           goto Begin1;
                        }
```

```
            }
    End Begin1
    if (max_pac == operation_pac)
      {
        operation_pac += (1-0.618) * operation_pac;
        goto Begin1;
      }
    elso if ( max_pac - operation_pac > accuracy * max_pac)
      {
        operation_pac = (1-0.618)*max_pac + 0.618 * operation_pac;
        goto Begin1;
      }
End Begin0;
```

APPENDIX D: Configuration

The file name of the configuration is defined as "config.model". The following format is given as an example:

FILENAME: config.model

```
PLAN_HORIZON 50
PERIOD_LENGTH 5
MAXIMUM_AND_MINIMUM_OPEN_SIZE 40 5
CURRENT_MININMUM_CUT_AGE
70 100 130 160 90
55 70 55 100 60
35 60 40 60 45
REGEN_MINIMUM_CUT_AGE
70 100 130 160 90
55 70 55 100 60
35 60 40 60 45
CUT_PRIORITY 7
35 55 75 95 115 135 155
EXCLUSION_PERIOD
15 15 15 15 15
15 15 15 15 15
15 15 15 15 15
SITE_CLASSIFICATION 1
REGENERATION_LAG
```

0 0 0 0 0

0 0 0 0 0

0 0 0 0 0

SITE_IMPROVEMENT

1 1 1 1 1

2 2 2 2 2

3 3 3 3 3

SPECIES_COMPOSITION

1 2 3 4 5

1 2 3 4 5

1 2 3 4 5

BLOCK_SHAPE_CONTROL 0

ACCURACY 0.005

OUTPUTFILE

p50_98 p50_2003 p50_2008 p50_2013 p50_2018 p50_2023 p50_2028 p50_2033 p50_2038 p50_2043

Where:

- Planning horizon

Planning horizon is the timber supply plan length (year), for example, 50 year plan. The file format is:

PLAN_HORIZON 50.

- Plan Period Length

It is common that the planning horizon is often divided into a number of periods with the same length such as five years or ten years and son on. Its file format is:

PERIOD_LENGTH 5

Where 5 years is assumed as period length.

- Maximum and Minimum Opening Sizes

Maximum opening size is a constraint that is used to limit clearcut block size. Its value is regulated by government agency or forest industries. In Canada, each province may have its own maximum opening size. Minimum opening size is designed to achieve the feasible timber supply. The detailed discussion was given in the section 3.3.1. The format in the configuration file is described as follows:

MAXIMUM_AND_MINIMUM_OPEN_SIZE 40 5

Where 40 hectare and 5 hectare are respectively assumed as maximum opening size and minimum opening size.

- Minimum Cut Age

There are two minimum cut age constraints: current and regenerated minimum cut ages determined by using current and regenerated yield curves or tables based on site and species. The formats are created as follows:

Age	species 1	species 2	species 3	species 4	...
site 1					
site 2					
site 3					
.					
.					
.					

Table 18. Current minimum cut age

Age	species 1	species 2	species 3	species 4	...
site 1					
site 2					
site 3					
.					
.					
.					

Table 19. Regenerated minimum cut age

- Cut Priority Rule

That the oldest age is first is used as cut priority rule. There are several ways to realize this rule. The following format is an example designed for the cut priority rule:

CUT_PRIORITY 7

35 55 75 95 115 135 155

Where 35, 55, 75, 95, 115, 135, 155 are ages (years) for cutting. 7 is the number of the given ages or cut age intervals. The programming will automatically form the harvest queue ranked by the intervals such as [155, 1000), [135, 155), [115, 135), [95, 115), [75, 95), [55, 75), and [35, 55).

- Exclusion Period

As described in the section 3.3.2, exclusion period is established to control harvesting time for neighbor cut blocks. The exclusion period may have different value for each site condition and species. The input format is given as follows:

Age	species 1	species 2	species 3	species 4	...
site 1					
site 2					
site 3					
.					
.					
.					

Table 20. The input format for exclusion period

- Site Classification

There are two types of site classifications: original site classification and site reclassification. For example, supposed there are three site classes such as fair, medium, and good, the reclassified site classes will be fair, medium, good, fair & medium, and medium & good. Its input format is designed as follows:

SITE_CLASSIFICATION 1

Where 1 means site reclassification. If 0 is input, it represents original classification.

- Regeneration Lag

Site treatment is evaluated by the regeneration lag (see the section 4.1). 0 represents no delayed time, that is, trees grow right after the site is harvested. Minus values represent that site treatment is poor or there is no any treatment at all, which needs more lagged time for new trees to start growing. If value is positive, that means that shelterwood system is used. The input format is:

Age	species 1	species 2	species 3	species 4	...
site 1					
site 2					
site 3					
.					
.					
.					

Table 21. The input format for regeneration lag

- Site Improvement

Site improvement determined by silvicultural plan means that the site quality is improved. For example, a fair site can be improved to be a medium site or good site. The input data for site improvement is related to a pair, (site, species). In this example, the values for site improvement represent no site improvement. If the value 1 located at (site 1, species 1) is changed to value 2, it means that the site quality located at site 1 and species 1 is improved from class 1 to class 2. The general input is formatted as follows:

Site class	species 1	species 2	species 3	species 4	.
site 1	1	1	1	1	
site 2	2	2	2	2	
site 3	3	3	3	3	
.					
.					
.					

Table 22. The general input format for site improvement

- Species Composition Control

Species composition is used to control the regeneration of trees and the species composition on the harvested blocks. This example represents no change for species composition after the first rotation. The values such as 1, 2, 3, 4, and 5 present the five types of species. Similar to site improvement, if the value 1 located at (site 1, species 1) is changed to 2, it means that the species 2 will replace species 1 down there after the site is harvested. Its generally input format is described as follows:

Species class	species 1	species 2	species 3	species 4	...
site 1					
site 2					
site 3					
.					
.					
.					

Table 23. The general format input for species composition control

- Block Shape Control

The spatial optimization model concurrently and dynamically blocks and harvests a forest when it is operated for timber supply analysis. Block shape control is necessary when the model is blocking a harvest stand. There are two options: 1 for approximated square shape and 0 for natural stand's shape (see the section 4.4.2). The input format is designed as follows:

BLOCK_SHAPE_CONTROL 0

- Convergent Accuracy

Convergent accuracy is used to control the solution accuracy of the algorithm. The accuracy is a relative accuracy such as percentage (%). The generally input format is as follows:

CONVERGENT_ACCURACY 0.005

Where 0.005 means that the relative accuracy is 0.5 %.

- Output File

The algorithm creates the output for each period in the planning horizon. That means, for a 50 year plan with period length of five years, the algorithm will produce the output with ten grid files. Therefore, it needs inputting ten output file's names provided by the users. Its input is formatted as follows:

OUTPUTFILENAME

name1 name2 name3 name4 ...

APPENDIX E: **Yield94.dat**

3 5 60
Decidous Fair site
0 0 0 0 0 0 0 0 0 0 0 0 0 9.69 26.96 44.23 58.085 71.94 83.795 95.65 105.665 115.68 104.555 93.43 82.31 71.19 60.065 48.94 37.82 26.7 15.575 4.45 2.225 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Mixedwood Fair site
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 5.845 11.69 26.12 40.55 54.045 67.54 80.05 92.56 104.11 115.66 126.3 136.94 146.625 156.31 165.29 174.27 182.525 190.78 198.365 205.95
Pine Fair site
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 17.98 27.215 36.45 45.575 54.7 63.625 72.55 81.21 89.87 97.735 105.6 113.53 121.46 129.04 136.62
Black spruce Fair site
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 9.65 17.315 24.98 32.635 40.29 47.83 55.37 62.345 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69.32 69 [illegible] 9.32 69.32 69.32
White spruce Fair site
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 13.4 27.98 42.56 [illegible] 95 97.82 110.885 123.95 136.35 148.75 160.46 172.17 183.175 19[illegible] 223.035 232.61 241.55 250.49 250.49 250.49 250.49 250.49 250 [illegible] 9 250.49 250.49 250.49 250.49 250.49 250.49 250.49 250.49 25[illegible] 250.49 250.49 250.49
Deciduous Medium site
0 0 0 0 0 0 0 0 0 0 0 34.93 56 77.07 95. [illegible] 6.76 169.88 181.075 192.27 173.785 155.3 136.81 118.32 99. [illegible] 5 7.4 3.7 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Mixedwood Medium site
0 0 0 0 0 0 0 0 0 0 0 0 0 0 16.99 33.98 54.235 74.49 92.585 110.68 126.82 142.96 157.28 171.6 184.315 197.03 208.245 219.46 229.47 239.48 247.78 256.08 263.985 271.89 278.96 286.03 292.375 298.72
Pine Medium site
0 0 0 0 0 0 0 0 0 0 0 33.18 58.12 83.06 105.945 128.83 149.495 170.16 188.415 206.67 223.04 239.41 253.715 268.02 280.485 292.95 304.29 315.63 325.69 335.75 344.805 353.86 362 370.14 377.465 384.79 391.405 398.02

Black spruce Medium site
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 24.66 37.865 51.07 64.04 77.01 89.68 102.35 114.515 126.68 138.545 150.41 161.845 173.28 184.26 195.24 205.755 216.27 226.21 236.15

White spruce Medium site
0 0 0 0 0 0 0 0 0 0 1.61 25.765 49.92 73.185 96.45 118.085 139.72 159.43 179.14 197.175 215.21 230.93 246.65 261.095 275.54 288.145 300.75 312.225 323.7 333.53 343.36 352.485 361.61 369.78 377.95 385.28 392.61

Deciduous Good site
0 0 0 0 0 0 9.73 53.81 97.89 130.995 164.1 189.545 214.99 235.04 255.09 269.775 284.46 297.185 309.91 320.325 330.74 298.935 267.13 235.33 203.53 171.73 139.93 108.125 76.32 44.52 12.72 6.36 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Mixedwood Good site
0 0 0 0 0 0 0 0 0 0 0 0 22.1 44.2 68.935 93.67 115.975 138.28 157.965 177.65 194.69 211.73 225.925 240.12 253.005 265.89 277.08 288.27 297.795 307.32 315.83 324.34 331.805 339.27 345.855 352.44 355.52 358.6

Pine Good site
0 0 0 0 0 0 0 0 56.01 93.69 131.37 165.125 198.88 228.16 257.44 282.475 307.51 328.815 350.12 367.8 385.48 400.15 414.82 428.03 441.24 452.64 464.04 473.875 483.71 492.36 501.01 508.62 516.23 522.955 529.68 535.66 541.64

Black spruce Good site
0 0 0 0 0 0 0 0 0 0 6.21 31.235 56.26 80.405 104.55 127.075 149.6 170.785 191.97 211.52 231.07 248.99 266.91 283.035 299.16 313.68 328.2 341.335 354.47 366.63 378.79 389.965 401.14 411.325 421.51 430.505 439.5

White spruce Good site
0 0 0 0 0 0 0 10.885 21.77 56.59 91.41 123.8 156.19 184.065 211.94 236.845 261.75 283.15 304.55 322.74 340.93 356.15 371.37 384.05 396.73 408.12 419.51 428.68 437.85 446.345 454.84 462.24 469.64 476.125 482.61 488.325 494.04