A SIMULATED ANNEALING METHOD FOR TARGET-ORIENTED FOREST LANDSCAPE BLOCKING AND SCHEDULING

By

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Abstract

The objective of this research was to conceptualize and develop a Target-oriented Forest landscape Blocking and Scheduling (TFBS) approach that can assist in solving complex forest landscape transformation problems. TFBS blocks and schedules forest treatments according to the requirements of transforming forest landscapes to desired states and projected forest stand dynamics. Timber flows are the results of the landscape transformations. The forest treatment schedules produced by TFBS not only sustain a wide range of non-timber resources but also maximize and maintain timber flows. TFBS can facilitate the forest management transition from timber harvesting regulation-based planning to desired state-oriented forest planning.

A desired state of a forest landscape is a state where all the resource layers on the landscape are in their desired states. The polygons created from overlaying multiple resource layers form the basic units for building the cutblocks. These dynamic cut blocks are combined over time to create patches and desired landscape structures. Age structures and patch size distributions are used as common indicators for all non-timber resources. Each resource layer is assigned one or more age structures and patch size distributions according to the management objectives.

To achieve the objectives of this research, a tool, Forest Simulation Optimization System (FSOS) was developed and tested on a simplified 400-polygon (10 ha per polygon) grid data set as well as a complicated 80,000 ha (18,000 polygons) Tree Farm in the Slocan Valley. The results spatially and temporally demonstrated the processes required in building blocks and patches, transforming forest landscapes to desired states and sustaining the desired states. FSOS is also compared to a time-step simulation model, ATLAS.

The results show that TFBS can produce strategies to transform forest landscapes to the same desired states with different initial states and different natural disturbance rates and patterns. TFBS simultaneously blocks and schedules the whole landscape for the entire planning horizon and the impacts of treatments on future landscape states are considered. Adaptive strategies are modified accordingly.

It was found that Simulated Annealing (SA) was an efficient algorithm for TFBS problems. No guarantee of optimality can be assured; however, SA can find good solutions within a reasonable time for complex problems. This is difficult or even impossible with directed search methods such as mixed integer programming.

Key words: Simulated annealing, target-oriented, landscape modeling, harvest scheduling.

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Chapter 1

Introduction

1.1 Problem Background

Forest resource management is shifting from a timber harvesting regulation-oriented approach to a target-oriented[1] approach. Although the origins of forest management have been rooted in the desire to sustain forests by supplying of one or more forest values, forest management has frequently failed to achieve its goals (Kimmins, 1995). One of the reasons for this failure is that forest management is usually based on harvesting regulations. For example, maximum opening size and adjacency constraints are typical rules used to prevent large clear-cut areas. Following these harvesting rules can lead, however, to an "undesirable" forest. In British Columbia, today's forests have been created primarily by following adjacency constraints during the last decade, and as a result, are not desirable in terms of wildlife habitat, visual quality, biodiversity[2] and natural disturbance regimes. This is because the adjacency regulations have led to fragmentation, and the fragmented forest may take a long time to revert back to a more natural forest.

[1] The target-oriented approach is a method of forest management that schedules forest treatments that transform forests into desired states.

[2] Biodiversity – Biodiversity (biological diversity) is the diversity of plants, animals and other living organisms in all their forms and levels of organization, and includes the diversity of genes, species and ecosystems, as well as the evolutionary and functional processes that link them (MOF, 1995).

Forest ecosystem[3] landscape[4] patterns on Canadian forests have evolved in an unplanned way, through a sequence of individual activities, even though many individual projects were normally well planned and executed. In current practice, forest management involves a "linear" decision-making process. Typically, a number of harvest and silviculture interventions that provide a sustainable wood supply for the working forest are first identified. Next, the interventions are gradually implemented, subject to a host of operating regulations, such as maximum opening size. In the linear approach, forest feedback control does not exist, since there is no stated forest objective as a basis for evaluating forest response to intervention. The harvest level objective may be achieved and the regulations will be followed. The forest that emerges, however, will not be measurable against a target. Management has not focused on achieving a forest condition, and in this case, according to Wardoyo and Jordan (1996), forest management does not exist.

Simulation models were developed and used to analyze the impacts of landscape patterns on different resources such as wildlife habitat, water and visual quality. These models follow a rule-based planning philosophy: "we do not know where we are going, but the roads will take us there". Often, this is not true. Numerous regulations may take us nowhere, and numerous roads may take us

[3] An ecosystem is any system composed of physical, chemical and biological process active with any space-time unit (Lindeman 1942). More definitions about ecosystem can be found in Kimmins' book "Forest Ecology" (Kimmins, 1987).

[4] A landscape is defined as a homogeneous area consisting of repeated interactive and interconnected ecosystems (Forman and Godron 1986).

places we might not want to go. Unfortunately, we may not realize it until we have arrived at the wrong place.

Nature cannot always create a sustainable forest landscape over the temporal and spatial scales desired by humans or required by wildlife, because of the variation in the occurrence and scale of natural disturbances such as wildfire, insects, disease and windthrow. The life spans of humans and animals are shorter than the rotation of most forests. Within a region, there could be 100% old growth and no young stands for the current generation of humans or wildlife. There could be 100% young and no old growth for the next generation of humans or wildlife in the same region following a large forest fire. Management intervention is, therefore, extremely important in achieving a sustainable forest over the spatial and temporal scales that humans and wildlife desire.

Simply protecting the forest from harvesting will not necessarily retain current resource values because forests are not static. All stands are going through a series of developmental stages from regeneration to old stands and back to regeneration. New trees will grow up to replace their parents. Natural disturbances from fires, insects, disease and windthrow will probably consume the old forest sooner or later. Today's old growth will be tomorrow's young growth; today's young growth will be tomorrow's old growth; today's connection will be tomorrow's isolation; and today's isolation will be tomorrow's connection.

With proper harvest scheduling, the loss to fire, insects, disease and windthrow can be greatly reduced. In Canada, between 1979 and 1993, fire, insects and disease affected more area in the commercial forest than harvesting

(Natural Resources Canada, 1996). On average, natural disturbances affected 0.6% of the forest annually, while only 0.4% of the forest was harvested (Natural Resources Canada, 1996). Ideally, stands should be harvested before fire, insects, windthrow or disease destroy them.

Proper scheduling of harvest units may help to reduce timber production costs. Integrated resource management regulations are expensive. A conservative estimate of the annual cost to the people of British Columbia of implementing the B.C. Forest Practices Code is $2.1 billion, equal to $570 per B.C. resident (Haley, 1996). These costs include planning, administration, legal expenses and increased operational costs associated with building and maintaining more roads, road deactivation, logging practices, and modified silvicultural systems (Haley, 1996).

Current forest management is complex. Many different interest groups express their concerns about forest management. For example, wildlife experts want some areas to be maintained for habitat and local communities want some areas to be maintained for aesthetic values. Environmentalists may require that a specific ecosystem be protected. Different groups have different indicators for measuring forest conditions. These different values greatly increase the complexity of managing forests. Further complexity is added by dynamic growth of the forest through time.

Many forest management problems are caused by conflicts between historical forest management practices and new regulations. The current forest states may be far from the desired state, and we cannot immediately transform

the forest to the desired state. Moreover, the desired forest states may change over time. However, by properly scheduling harvest units, we can moderate the conflict, reduce the impacts of new regulations and gradually transform the forest landscape to the desired state.

Nelson (1993) viewed the integrated resource management problem as a puzzle, where various non-timber and timber interests represent the pieces. The question is how all these different pieces fit together in timber supply? If these different values fit together properly, all values can be achieved and maintained; if these values do not fit together properly, at a minimum, some outputs will decrease, and at the worst, a feasible solution may not be achievable. Scheduling harvest units is like solving the puzzle. If the harvest units are scheduled properly, there is a better opportunity to maintain all values. If a harvest unit is not treated at the proper time, it will not produce its maximum value and it may adversely affect the scheduling of adjacent stands.

Harvest scheduling problems are difficult to solve because of the size of the problem and the constraint structure. The number of possible treatments can grow very large, and finding a good solution becomes computationally difficult. These large-size, non-linear combinatorial optimization problems have been impossible to solve using direct search methods. The current spatial constraints in British Columbia make complicated scheduling problems (i.e. multiple-layer stand age structures and patch size distribution requirements).

Regulation-based, time-step simulation models can only generate a number of scenarios and assess the consequences of alternative strategies

(Gustafson and Crow, 1996). In other words, the simulation models in themselves do not produce strategies - they only quantify consequences of defined strategies.

Considerable effort has been directed towards heuristic search techniques. The heuristic search approach is able to produce near optimal or high quality solutions with acceptable computing time and resources.

There are numerous references on regulation-oriented forest harvest scheduling methods. However, there is little reference available for target-oriented approaches. Forest ecosystem management has to change because of new knowledge and new non-timber values. A target-oriented approach is urgently needed for the new management of forest ecosystems and landscapes.

1.2 Objectives

The objectives of this thesis are:

- To develop common indicators for non-timber resources at the landscape level;
- to develop a target-oriented Forest harvest Blocking and Scheduling (TFBS) method that is capable of transforming forest landscapes to desired states (as measured by the indicators) and sustaining the desired states while maximizing timber flows; and
- to apply TFBS and explore tradeoffs between production of timber and non-timber objectives in case studies.

The design of TFBS is governed by the following principles:

1) TFBS will simultaneously block and schedule treatments to meet timber and non-timber objectives instead of following strict harvest regulations.
2) It will include age-structure and patch-size distribution targets, which are two common indicators used to measure resource values on the landscape.
3) Polygons created from overlaying multiple resource layers will be the basic units to build harvest blocks, and the blocks can be combined over time to form patches.
4) TFBS must be able to create flexible strategies that can adapt to natural disturbance and other uncertainties (Walters, 1986).
5) TFBS must include objective weights that can be altered to control how quickly and strictly targets are achieved.
6) TFBS must include multiple treatments over time so that multiple rotations can be modeled.
7) Treatments will be scheduled by year, so that any reporting period can be selected (1-year, 5-year, 10-year, etc.).

The remainder of this thesis is organized by the following chapters:

1. Chapter 2 reviews the literature on forest harvest scheduling methods, models and algorithms used in forest resource planning.

2. Chapter 3 describes the simulated annealing algorithm used in the model. It describes how objectives are formulated for timber, age structures, and patches.
3. Chapter 4 contains sensitivity analysis of TFBS using a 400-polygon sample data set, including cooling schemes, road costs, objective weights, and natural disturbance.
4. Chapter 5 is a case study based on a tree farm (18,000 polygons and 80,000 hectares) in the Slocan Valley. This case study has 46 resource layers (such as watersheds, wildlife, visuals) and has many conflicting objectives. Several scenarios are run under different objective weighting schemes. Results are also compared to a time step simulation model.
5. Finally, conclusions and recommendations are in Chapter 6.

Chapter 2

Literature Review

Most forest harvest scheduling methods share two common characteristics: 1) they follow harvest regulations to schedule harvest blocks, and 2) they block and schedule forest treatments by separate processes. The blocks are laid out for the whole area (and the entire planning horizon) according to current forest states and regulations. Regulation-based models are used to schedule the predetermined blocks.

A common objective of forest planning has been to generate a long-term harvest schedule that maximizes the volume harvested (or the net profit), subject to numerous constraints. Typical constraints are: 1) the maximum clear-cut size, and 2) the minimum exclusion period between adjacent clear cuts. In addition, harvest flow and budget constraints are usually added to control resources in each time period. The need to deal with adjacency constraints has been presented in many papers (Synder and Revelle, 1995; Thompson et al., 1973; Jamnick and Walters, 1991; Jones et al., 1991; Torres et al., 1990; Barahona et al., 1992).

There have been numerous publications during the last few years about regulation-based harvest scheduling methods based on different optimization techniques. Linear programming (LP) was one of the first methods introduced (Navon, 1971, Thompson et al., 1973). FORPLAN (Johnson et al 1986, and Kent 1985) was designed to address the problem of optimal scheduling of harvests with linear programming. In addition to solution difficulties, infeasibility occurred

frequently. Infeasibility in FORPLAN can arise from a number of causes, and these are often difficult to identify in tightly constrained problems (Kent, Kelly and Flowers 1985). Recently, dynamic programming was used for solving large-scale adjacency problems (Borges et al., 1999).

2.1 Mixed Integer Programming (MIP)

MIP is a specific case of linear programming where some variables are restricted to integer values. There are a few of studies that applied MIP to harvest scheduling (Kirby, 1986, Nelson and Brodie, 1990, and Weintraub et al, 1995).

MIP has had limited success because of restricted computing resources as well as difficulties in formulating the problem and interpreting the results (Boston and Bettinger, 1999, Hof et al 1994). In response to problem-size limitations, heuristic techniques have been designed for generating near-optimum solutions.

2.2 Heuristic Approaches

An example of a simple heuristic technique is the sampling approach called Monte Carlo Integer Programming (MCIP) (Nelson and Brodie (1990), O'Hara et. al. (1989), Clements et. al. (1990)). This approach is a biased sampling scheme designed to generate feasible solutions. The success of Monte Carlo Integer Programming is directly related to the number of sample solutions generated. If the sample size is very large, MCIP is more likely to obtain near-

optimal solutions. However, larger sample sizes require longer computing times. The advantage of Monte Carlo Integer Programming is its ability to generate feasible solutions in a short time. However, it is quite inefficient at finding near-optimal solutions. As more problem-specific information becomes available, more efficient algorithms can be designed to take advantage of specific structures. Prioritizing harvest units within simulation models has produced good results (O'Hara et al. 1989, Nelson and Finn, 1991). Prioritized simulation combined with random search methods has also been applied to tactical forest planning problems (Sessions and Sessions, 1991).

Other heuristics including Interchange, Simulated Annealing, Tabu Search and Genetic Algorithms begin with a random solution (or a set of random solutions) and successively improve upon it (or them). These improvement methods lead to near-optimal solutions, without the need to generate a large sample, as is the case with the MCIP approach. The time needed to improve an initial solution is less than the time needed to generate a large number of MCIP solutions, so these improvement methods provide high quality solutions in a relatively short time. The differences lie in their strategies for moving towards better solutions and avoiding convergence on local optima.

Comparisons of interchange, simulated annealing, and Tabu search were reviewed by Murray and Church (1993). Monte Carlo Integer Programming (MCIP), Simulated Annealing (SA) and Tabu Search (TS) were applied to solve four harvest-scheduling problems (Boston and Bettinger, 1999). The results showed that SA found the best solutions for three of the four problems while TS

found the best solution for one of the four problems. In the next few sections, I review these four common heuristic search algorithms in detail.

2.2.1 Interchange

Interchange is a random search method, which is also called the hill-climbing algorithm (Murray and Church, 1993, and Liu, 1985) because only improvement transformations in the solution space are accepted. There have been many successful applications of interchange procedures for 0-1 integer-programming problems. The success of the interchange approach depends primarily on the starting point. The interchange process begins with a feasible solution and maintains feasibility throughout the solution transformations. If there is an adjacency constraint violation, then polygons that violate the rules are set to a non-harvest status. If the new solution maintains feasibility for all other constraints, then its objective function is evaluated. If the transformation results in an improvement, the new solution becomes the current solution. The process continues until no improved transformation can be found. Interchange is simple and works very well for harvest scheduling problems (Liu, 1995). The disadvantage of the interchange procedure is that it is likely to get trapped at local optima.

2.2.2 Simulated Annealing (SA)

Simulated annealing is analogous to metal annealing. Metal annealing is the process of particle arrangement when moving from a high-energy state to

low-energy state. In a high-energy state, particles are active and able to move freely. As temperature gradually decreases, the particle position gradually freezes. Kirkpatrick et al (1983) first applied simulated annealing algorithms to combinatorial optimization problems based on the work of Metropolis et al. (1953). Since 1980, simulated annealing has been used in many fields such as the design of computer circuits, and transportation networks. The key issue in annealing is how to control the cooling process in order to bring the solid to a low energy state while maintaining the desired particle arrangement.

SA differs from interchange in its moving strategy, which attempts to avoid converging on a local optimum. SA begins with a high probability of accepting inferior moves and this probability gradually decreases to zero after a number of iterations. SA has been successfully used for harvest scheduling problems (Lockwood and Moore, 1993, and G. Liu and Nelson 1994, Boston and Bettinger, 1999, Kong 1999).

2.2.3 Tabu Search Algorithm

Tabu search has enjoyed numerous successful applications in a wide variety of problem areas (Glover, 1989, Hertz and de Werra, 1990). The tabu search algorithm has been used successfully for solving adjacency problems (Brumelle, et al., 1998, Murray and Church, 1993, Boston and Bettinger, 1999). Murphy (1999) also used Tabu search for allocating stands and cutting patterns to logging crews.

Tabu search differs from simulated annealing and interchange in its strategies to overcome local optimality (De Werra and Hertz, 1989). Rather than relying on a functional probability of accepting non-improvement solutions, Tabu search systematically forces the process into new regions of the solution space using short-term and long-term memory search strategies (Glover, 1989, 1990). Short-term memory keeps the process from cycling back into a locally optimal solution that has been identified, and long-term memory is used to boost the process into a solution region that has not been previously encountered.

2.2.4 Evolution Programs

During the last 3 decades, there has been a growing interest in problem solving systems based on the principles of evolution and genetics. Such systems maintain a population of potential solutions; they have some selection process based on fitness of individuals, and some recombination operators (Michalewicz, 1991). The evolution program is a probabilistic algorithm that maintains a population of individuals where each individual represents a potential solution to the problem. Each solution is evaluated to give a measure of its "fitness". Then, a new population is formed by selecting the more fit individuals. Some members of the new population undergo transformations by means of "genetic" operators to form new solutions. After a number of generations the program converges - the best individual hopefully represents the optimum solution. The two common operators are: 1) mutation, which introduces new information into the population, and 2) crossover, which spreads the new information throughout the population.

Clearly, many evolution programs can be formulated for a given problem. Such programs may differ in many ways; they can use different data structures for encoding a single individual, different "genetic" operators for transforming individuals, different methods for creating an initial population, different methods for handling constraints of the problem, and different parameters (population size, probabilities of applying different operators, etc.). However, they share a common principle: a population of individuals undergoes transformations, and during this evolution the individuals strive for survival. The population undergoes a simulated evolution: at each generation the relatively "good" solutions reproduce, while the relatively "poor" solutions die.

Evolution programs are based entirely on the idea of genetic algorithms; the difference is that evolution programs allow any data structure (i.e. chromosome representation) to be used together with any set of "genetic" operators. Classical genetic algorithms use a fixed-length binary string for the individuals and two genetic operators: binary mutation and binary crossover.

For harvest scheduling problems, evolution programs are not as efficient as simulated annealing. Crossover operators with adjacency constraints damage the solutions, and it requires a lot of time to repair the damaged solutions. If repairs are not done, considerable time is wasted evaluating infeasible solutions (Liu, 1995).

Chapter 3

Simulated Annealing Algorithm Applied to Target-oriented Forest Blocking and Scheduling

Applications of simulated annealing, hill climbing and evolution programs to forest harvest scheduling problems were explored in Liu (1995). These methods are random search techniques that start with an initial solution and improve it gradually. Evolution programs simultaneously work with a population of solutions (chromosomes) while simulated annealing works with only one solution. I have found that simulated annealing is relatively simple and provides good solutions within a reasonable time and computing resources.

In order to apply the Target-oriented Forest landscape Blocking and Scheduling (TFBS) approach, I have developed a spatial Forest Simulation and Optimization System (FSOS) model. This model is a spatial landscape level model. The spatial data are stored in original GIS formats such as IDRSI, MOSS and ArcView GIS shape files. The remaining data are stored in MS ACCESS database tables. A spatial data set that includes the proposed harvest units and the road network information is a prerequisite for this model. FSOS uses simulated annealing to schedule harvest units and design forest landscapes according to a wide range of spatial and temporal targets.

The fundamental difference between FSOS and rule-based, time step simulation models is that FSOS focuses on creating a desired forest landscape according to a set of objectives, whereas rule-based models generate a harvest schedule and a forest landscape subject to a series of rules.

In this chapter, I will identify two common indicators for all the non-timber resources, present the blocking and scheduling process, and describe the simulated annealing algorithm.

3.1 Forest Landscape Non-timber Resources

Non-timber values include biodiversity, wildlife habitat, visual quality, and water quality. It is difficult for forest managers to find a common indicator for these resource values. Before developing the target-oriented forest landscape blocking and scheduling approach, I will analyze and summarize the non-timber resources and identify some common indicators.

3.1.1 Wildlife Habitat and Biodiversity

The Forest Practices Code (MOF, 1995) acknowledges the importance of landscape ecology concepts by enabling district managers to designate planning areas called landscape units, each with specific landscape objectives. The Biodiversity Guidebook (MOF, 1995) recommends procedures to maintain biodiversity at both the landscape and stand levels. This approach, which uses the principles of ecosystem management, tempered by social considerations, recognizes that the habitat needs of most forest and range organisms are met if a broad range of age classes and landscape patterns are maintained across landscapes. Table 3.1 shows a sample desired age class structure and Table

3.2 shows a sample patch[5] size distribution as identified in the Biodiversity Guidebook (MOF, 1995).

Table 3.1 - Sample age class structure (% area within a layer).

Young (<40 years)	Mature (>80 years)	Old (>250 years)
<23%	>54%	>13%

Table 3.2 – Sample patch size distribution.

Patch size (ha)	% area within an age class of a layer
<40	30-40
41-80	30-40
81-250	20-40

3.1.2 Visual Quality

The Recreation Branch of the BC Ministry of Forests produced guidelines for recreation resources in timber supply analysis. To achieve visual landscape objectives, young stand and opening size constraints on harvesting are used when clear-cutting. The maximum percentage harvest permitted for each of the visual quality objectives is set to reflect current management strategies and the conditions of the particular forest with regard to landscape sensitivity and existing visual conditions. All forested areas of the land base, even those not available for harvest (inoperable) are factored into the calculation of cover constraints to reflect their impact on the visual landscape. The impact of these inoperable areas is dependent on their spatial arrangement.

[5] A patch is a relatively homogeneous nonlinear area that differs from its surroundings (Forman and Godron 1981)

3.1.3 Watershed Protection

Watershed protection is usually addressed by employing disturbance constraints with green-up heights based on hydrologic recovery, and maximum disturbance rates based on provincial or regional guidelines for watershed management. Watershed protection at a landscape level can also be represented by age class structure and patch size distribution.

3.1.4 Two Common Indicators for Non-timber Resources

From the above description, non-timber resource values at the landscape level can be represented by the following indicators (Figure 3.1):

1) age class structure, and

2) patch size distribution.

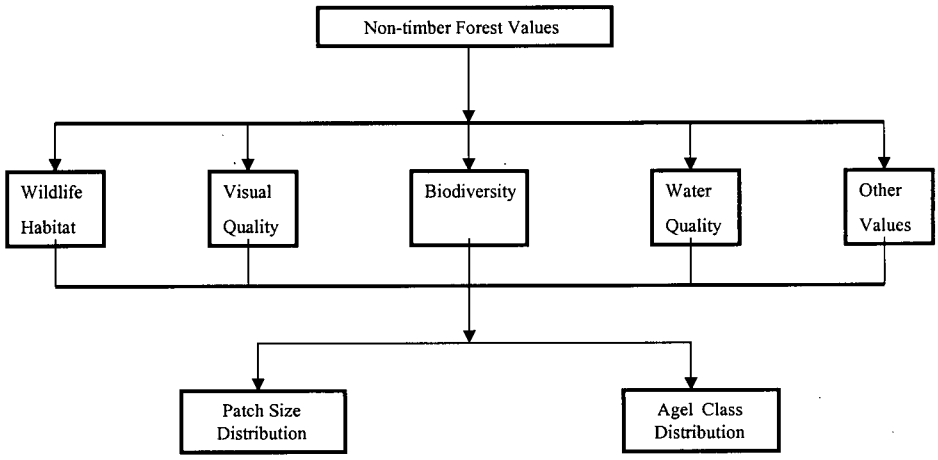


Figure 3.1 - Representation of non-timber values at the landscape level by age class structure and patch size distributions.

Age Class Structure

'Age class structure' is defined as the percentage of an area occupied by various age classes. In British Columbia, age class structure classifications are taken directly from the BC MOF Biodiversity Guidebook (1995) and are applied by Natural Disturbance Type (NDT[6]) within Landscape Units.

Patch Size Distribution

'Patch size distribution' is defined as the percentage of an area occupied by various patch sizes. The patch can be defined by age, cover type or the combination of age and cover type.

[6] NDT (Natural Disturbance Type) is defined according to the occurring frequency of stand-initializing events. NDT1 = ecosystem with rare stand-initializing events, NDT2 = ecosystem with infrequent stand-initializing events, NDT3 = ecosystem with frequent stand-initializing events (MOF, 1995).

3.2 Target-oriented Forest Blocking and Scheduling (TFBS)

The TFBS process begins with the selection of management objectives for resources such as visual quality, water, wildlife and biodiversity. Committees of experts in each of these resource areas define the states necessary to meet the specified objectives, and determine age structures and patch size distribution targets. The user ranks the relative importance of these two key parameters (age class structure and patch size distribution) relative to each other and to four other model output parameters listed below:

1) Total Volume Production - This is a measure of the total volume harvested in the planning horizon (i.e. 200 years),

2) Even Volume Flow - This is a measure of the variation in harvest volume between periods,

3) Cut Block Size - This value is constrained within a specified range to eliminate small inoperable cutblocks or excessively large ones, and

4) Timber Values and Production Costs – These values include timber market values and production costs (logging, transportation and road construction) that can be used in short-term planning.

Each resource layer on the landscape can have a target age class structure and the stands of each age class can have a patch size distribution (Figure 3.2).

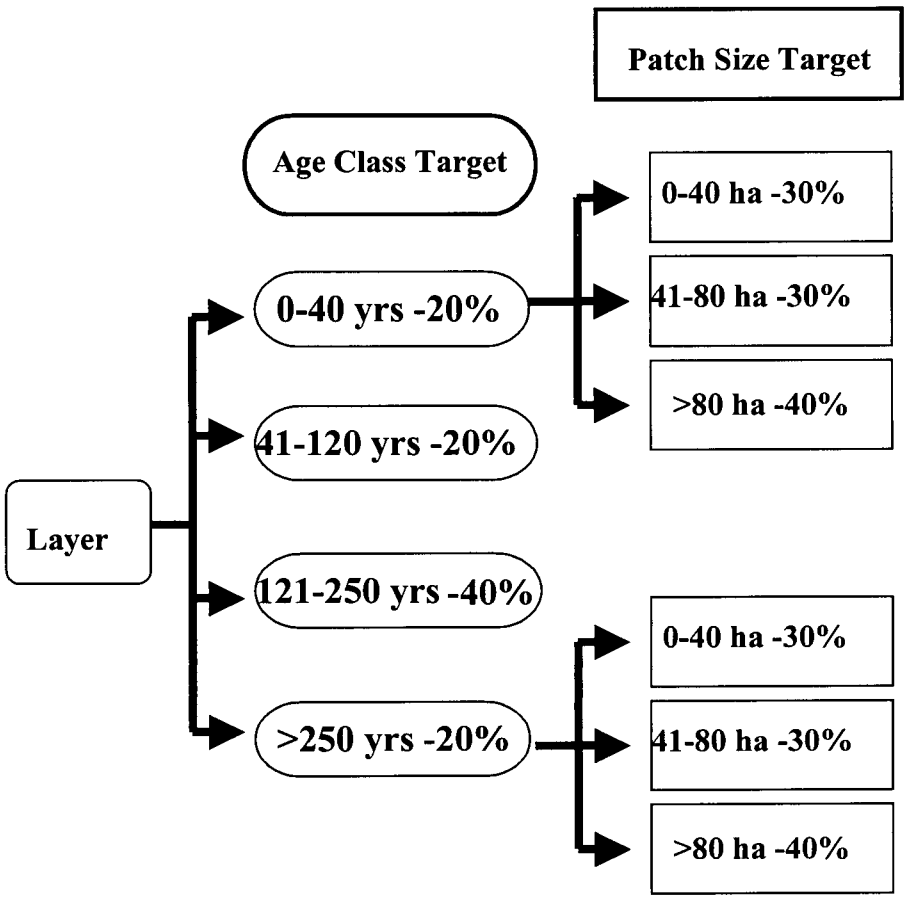


Figure 3.2 – An example of target age structures and patch size distributions.

Figure 3.3 depicts two sample forest landscape states. State 1 represents the current forest landscape, while state 2 represents the desired forest landscape. State 1 is a dispersed small-patch landscape and state 2 is an aggregated large-patch landscape. The transition targets (i.e. wildlife habitat, water quality and visual quality) will be defined by experts according to desired states represented by age class structure and patch size distributions. The

transition process must also meet certain biological and economic requirements such as minimum harvest age, harvest priorities and timber flows.

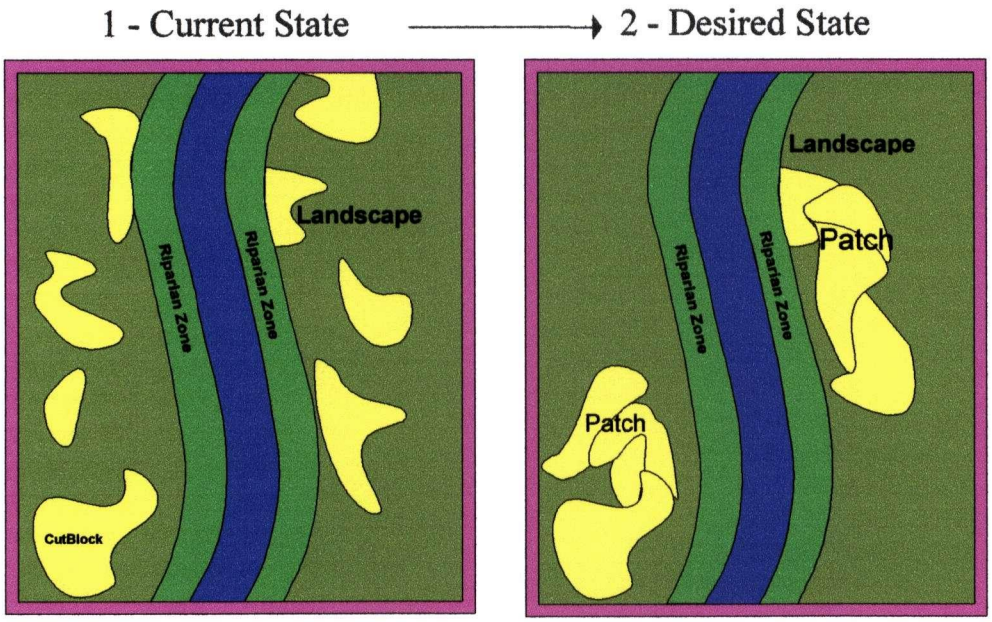


Figure 3.3- Forest landscape transformations.

TFBS combines short-term and long-term planning into one process (Figure 3.4). Projections can be made for hundreds of years, and 20-year and 5-year plans can be extracted without further analysis because FSOS schedules all management periods simultaneously. Simultaneous blocking and scheduling for the entire planning horizon allows tradeoffs between the long-term and the short-term.

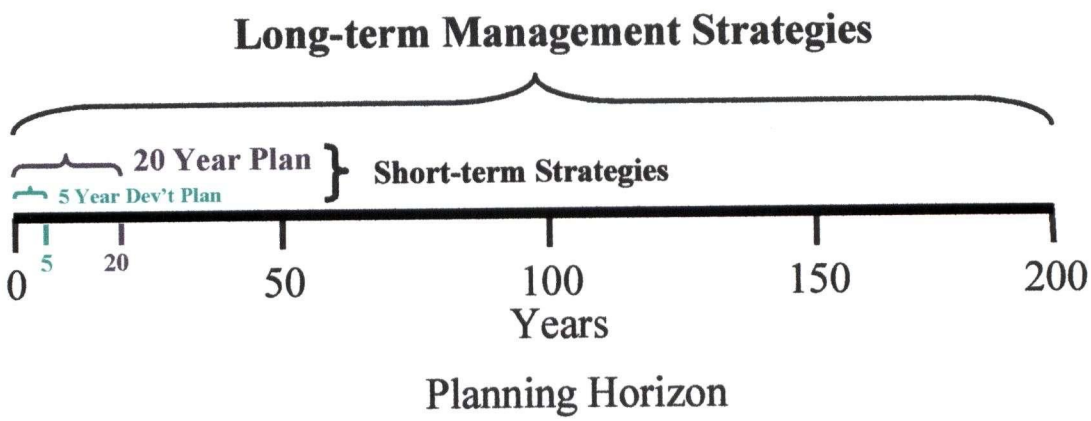


Figure 3.4 – Combined short- and long-term forest planning.

Weighting Multiple Objectives

Timber and non-timber values are included in the objective function. The objective is to maximize the difference between the timber value and the sum of the weighted deviations of non-timber values from their respective targets. Target values are set for the indicators that measure non-timber values. The model calculates a "penalty" based on the difference between the target for each parameter and the value actually attained in each period. The "penalties" are summed for all periods and weighted according to user preference. To minimize the total "penalty" over the planning horizon, the model attempts to achieve targets sooner for highly weighted values as opposed to lower weighted values. Harvest priorities can be applied to stands with a high probability of damage by fire, insects or windthrow.

Block and Patch Building Strategies

To provide the flexibility in building blocks and patches, the forest is partitioned into polygons through an overlay process (Figure 3.5).

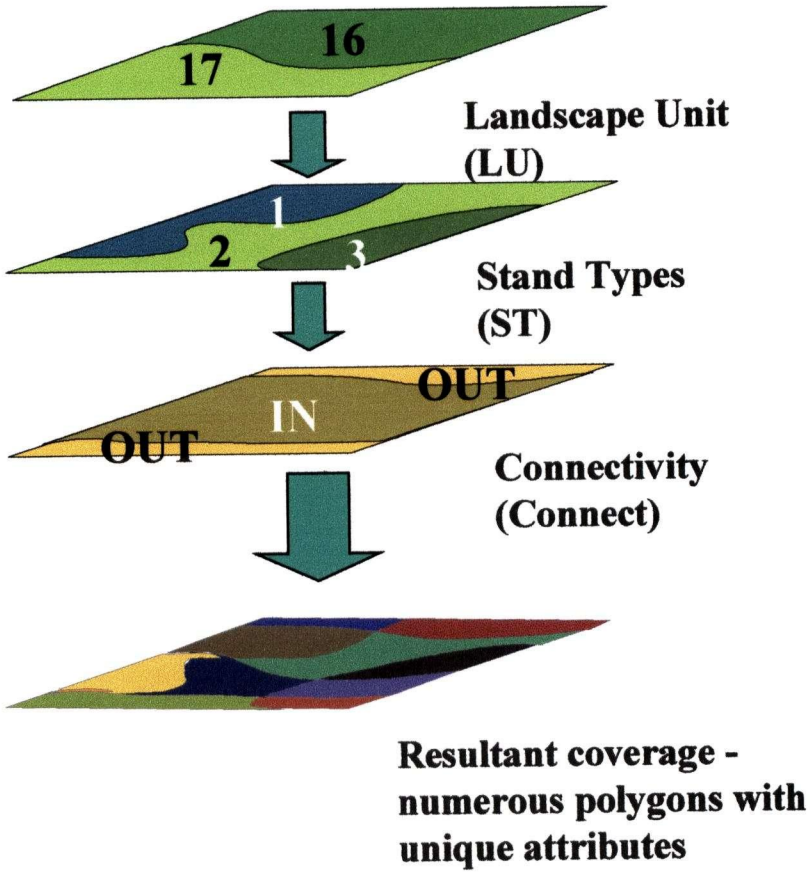
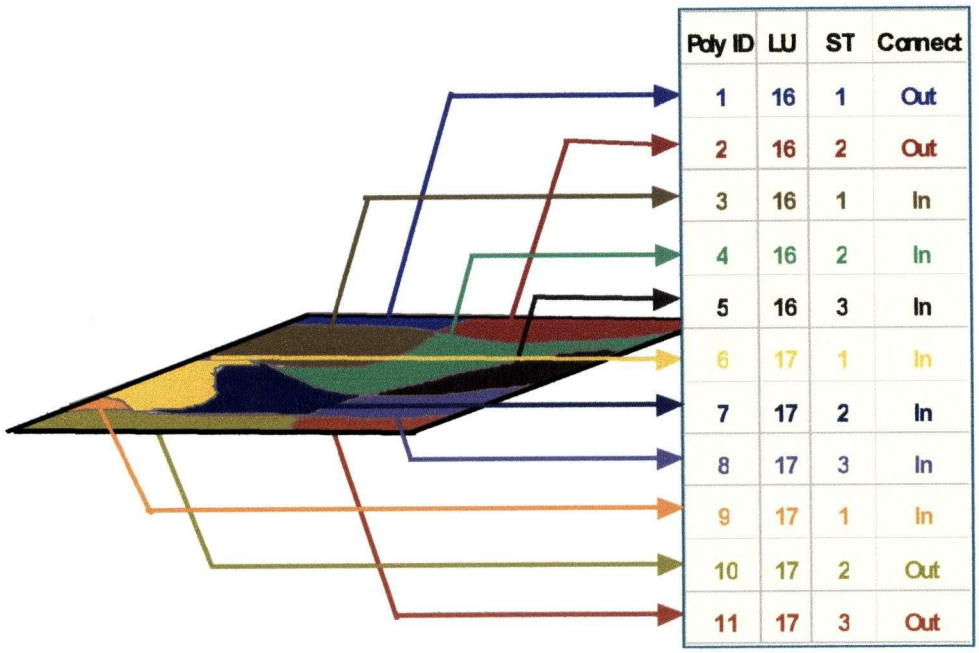


Figure 3.5 – The process that generates resultant polygons.

Each polygon has attributes (e.g. current age, area, stand type, reserve status, etc.) that are essential for landscape level modeling (Figure 3.6).



Poly ID	LU	ST	Connect
1	16	1	Out
2	16	2	Out
3	16	1	In
4	16	2	In
5	16	3	In
6	17	1	In
7	17	2	In
8	17	3	In
9	17	1	In
10	17	2	Out
11	17	3	Out

Figure 3.6 - Resultant polygons and attributes.

The limitation of many models has been in how they define a patch. The term "patch" has been synonymous with "cut block". So to create large patches, these models have to create large cut blocks.

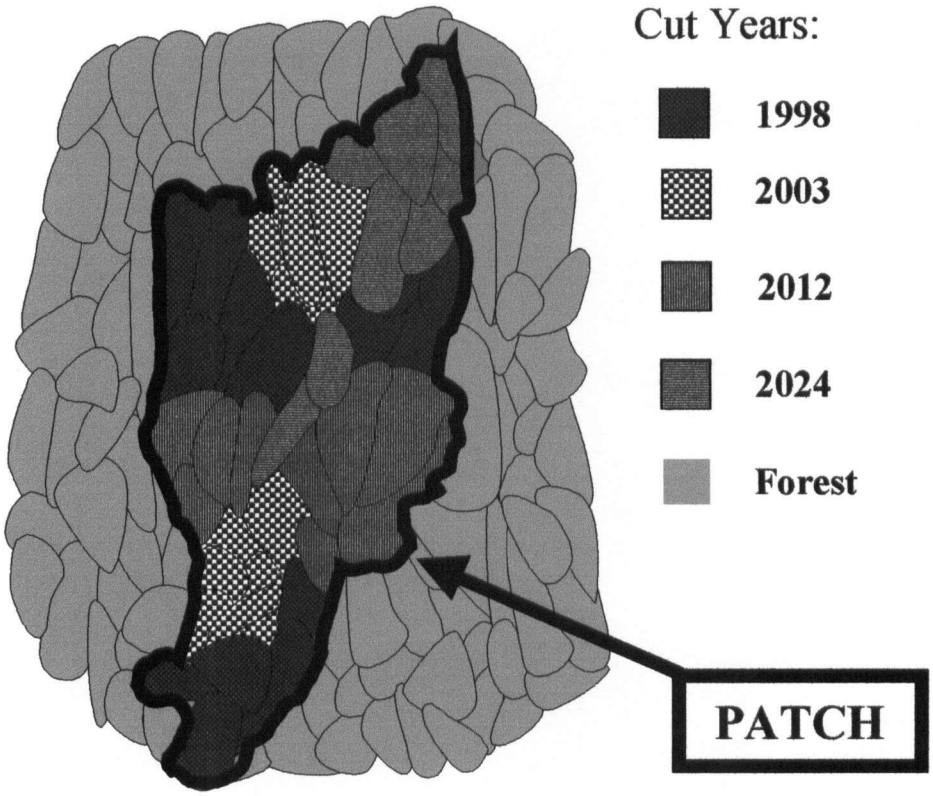


Figure 3.7 – Building blocks and patches with resultant polygons.

In the FSOS model, the terms "cut block" and "patch" are distinctly different. Patch is defined as a contiguous area of forest cover in a defined age

class and with common forest cover attributes, such as species composition (MOF, 1995). The resultant polygons are basic elements, which can be combined to form harvesting blocks, which can amalgamate to build patches over time. This gives great flexibility in harvest scheduling because adjacent polygons can be added or subtracted from the simulated cut block through successive iterations. Figure 3.7 is an example of a young patch that is the result of 9 cut blocks created over 4 harvest periods (1998-2024).

3.3 Simulated Annealing Applied to TFBS

The three major elements of simulated annealing include: 1) solution representation, 2) solution evaluation, and 3) solution transformation. In the next sections, I will describe these elements.

3.3.1 Solution Representation

The solution can be represented by placing the polygon numbers in a one-dimension array according to the cutting sequence (Liu, 1995). For multiple-rotation scheduling problems, one-dimension arrays will not work and the solution has to be represented by a 2-dimensional array (Table 3.3). The 2-dimensional array shows the cutting times of each polygon during the planning horizon. Additional data sets hold polygon attributes (age, area, adjacent polygons, road network access, etc.) necessary for interpreting the solution.

Table 3.3 - Example of harvest schedule represented by a 2-dimensional array.

Polygon Id	Cut Year			
1	2000	2095	2212	...
2	2050	2165	2255	...
3	2070	2180	2275	...
4	2045	2135	2260	...
...				

3.3.2 Solution Evaluation

To evaluate the solution, additional polygon attributes are used to calculate the achieved values for each target over the entire planning horizon. There are six categories of targets: 1) patch size distributions, 2) age structures, 3) cut block sizes, 4) timber flows, 5) total timber volume, and 6) timber value and production costs. The mathematical formulations are described below.

3.3.2.1 Patch Size Distribution

When the patch size distribution deviates from the desired patch size distribution, penalties are imposed (Figure 3.8 and equation 3.1).

The patch size distribution penalty is:

$$X = \sum_{p=1}^{Pds} \sum_{l=1}^{Layers} \sum_{j=1}^{AgeGrp(j)} \sum_{k=1}^{Sizes(l,j)} PatchP_{pljk} \qquad (3.1)$$

Where,

p is the period (p = 1,2,3 ... Pds);

l is the layer (l = 1,2,3 ... Layers);

j is the age class in layer l (j = 1,2,3 ... AgeGrps(l));

k is the patch size group in age class j of layer l (k = 1,2,3 … Size(l,j));

X is the total patch size distribution penalty caused by the deviation of the actual area from the desired area (all patch sizes, all age classes and all layers during all periods);

$PatchP_{pljk}$ is the penalty caused by the deviation of the actual area from the desired area of patch size k of age class j of layer l at period p (equation 3.2);

Pds is the total number of planning periods;

Layers is the total layer number;

AgeGrps(l) is the number of age classes in layer l; and

Sizes(l,j) is the total number of patch sizes in age class j of layer l.

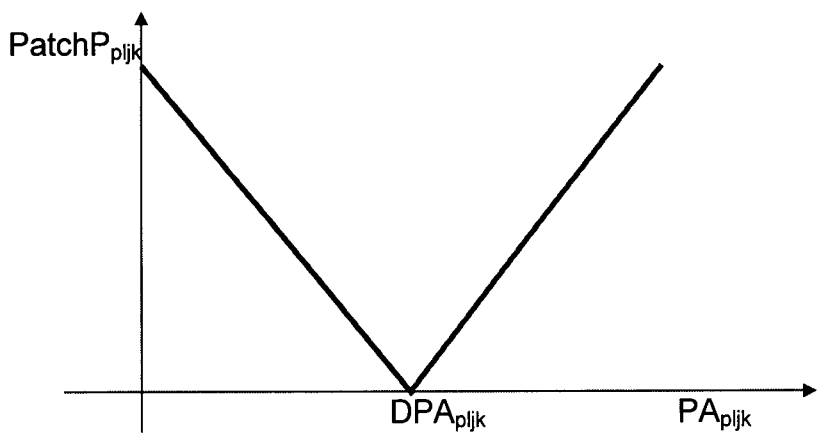


Figure 3.8 - Patch size distribution penalty curve.

$$PatchP_{pljk} = (1 + W_l)(1 + W_k)|DPA_{pljk} - PA_{pljk}| \quad (3.2)$$

where,

PA_{pljk} is the actual area of patch size k in age class j of layer l at period p;

DPA_{pljk} is the desired area of patch size k in age class j of layer l at period p;

W_l is the weight of layer l (the range is from 0.0 to 1.0 and the default value is 0); and W_k is the weight of patch size k (the range is from 0.0 to 1.0 and the default value is 0).

Figure 3.8 shows that the penalty is 0 when the actual area PA_{pljk} (of patch size k in age class j of layer l at period p) equals the desired number DPA_{pljk}. The penalty rate increases when the actual area PA_{pljk} deviates from DPA_{pljk}. The slopes of these two lines can be changed according to importance of these targets.

3.3.2.2 Age Class Structures

To control age class structure, a penalty value is incorporated in the objective function when age class structure deviates from the target age class structure (Figure 3.9 and equation 3.3).

The age class structure penalty for the whole solution is:

$$Y = \sum_{p=1}^{Pds} \sum_{l=1}^{Layers} \sum_{j=1}^{AgeGrps(j)} AgeStP_{plj} \qquad (3.3)$$

where,

Y is the total age class structure penalty caused by the deviation of actual area from the desired area (all age classes, and all layers during all periods);

$AgeStP_{plj}$ is the penalty caused by the deviation of actual area from the desired area of age class j of layer l at period p (equation 3.4);

Pds is the total number of planning periods;

Layers is the total number of layers; and

AgeGrps(l) is the total number of age groups in layer l;

$$AgeStP_{plj} = (1 + W_l)(1 + W_j)|DSA_{lj} - SA_{lj}| \quad (3.4)$$

where,

SA_{lj} is the actual area of age group j in layer l;

DSA_{lj} is the desired area of the age group j in layer l;

W_l is the weight of layer l (the range is from 0 to 1 and the default value is 0); and

W_j is the weight of age class j (the range is from 0 to 1 and the default value is 0).

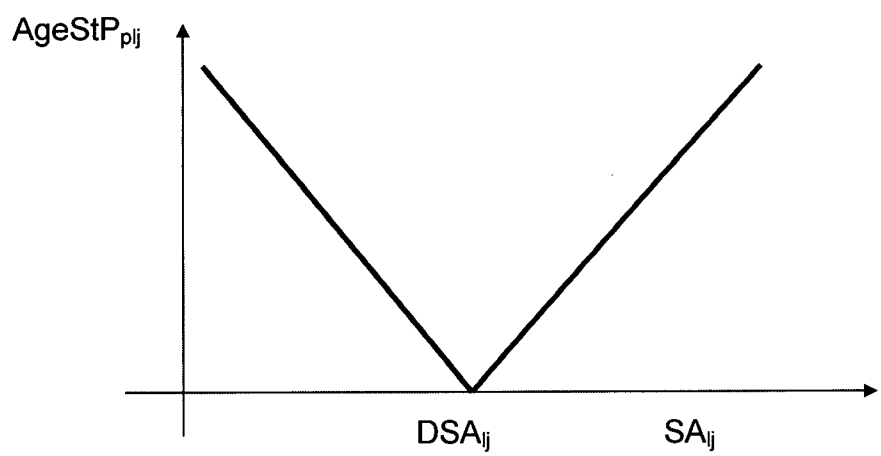


Figure 3.9 - Age class structure penalty curve.

Figure 3.9 shows that penalty is 0 when the actual area of age class j in layer l equals the desired area DSA_{lj}. The penalty increases when the actual area of age class j in layer l deviates from DSA_{lj}.

3.3.2.3 Volume Flow

To control the volume flow, a penalty value is incorporated in the objective function (Figure 3.10 and equation 3.5).

Total timber production over the entire planning horizon is:

$$V = \sum_{b=1}^{Polys} \sum_{c=1}^{Cuts(b)} P_{bc} \tag{3.5}$$

The volume flow penalty is:

$$Z = \sum_{p=1}^{Pds} FlowP_p \tag{3.6}$$

where,

P_{bc} is the volume from cut c of polygon b;

Cuts(b) is the total number of cuts of polygon b during the planning horizon;

Polys is the total number of polygons;

V is the total timber production from all cuts (equation 3.5);

p is the period (p = 1,2,3 ... Pds);

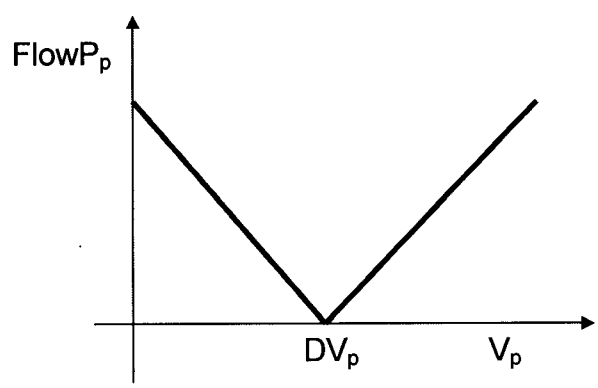


Figure 3.10 - Timber volume flow penalty curve.

Z is the total penalty caused by the deviation of the achieved volume from the desired volume in all periods (equation 3.6);

$FlowP_p$ is volume flow penalty caused by the deviation of the actual volume from the desired timber volume in each period p (equation 3.7); and

Pds is total number of planning periods.

$$FlowP_p = (1 + Wv_p) |DV_p - V_p| \quad (3.7)$$

where,

DV_p is the target volume in period p when the harvest volume flow target is applied, otherwise DV_p is the average volume flow achieved by the model;

V_p is the volume harvested in period p; and

Wv_p is the weight of period p (the range is from 0.0 to 1.0 and the default value is 0).

Figure 3.10 shows that penalty rate is 0 when the actual volume V_p equals the desired volume DV_p. The penalty rate increases when the actual volume V_p deviates from the desired volume DV_p.

3.3.2.4 Cut Block Size

To control cut block size, a penalty value is incorporated in the objective (Figure 3.11 and equation 3.8).

The cut block size penalty for the whole solution is:

$$S = \sum_{p=1}^{Pds} CsizeP_p \quad (3.8)$$

where,

S is the cut block size penalty caused by the deviation of actual size from desired size for all periods (equation 3.8);

$CsizeP_p$ is cut block size penalty caused by the deviation of achieved size from desired size in period p (equation 3.9); and

Pds is total number of planning periods.

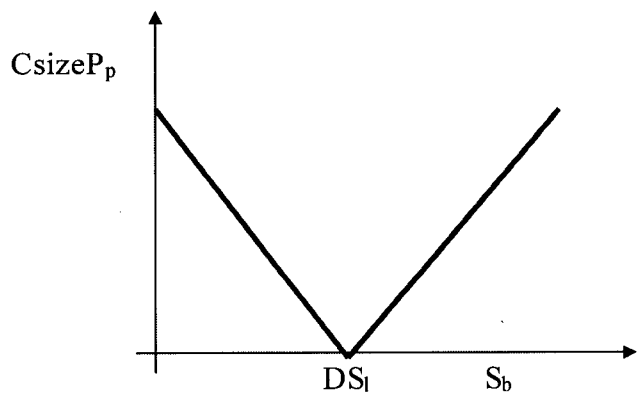


Figure 3.11 - Cut block size penalty curve.

$$CsizeP_p = \sum_{l=1}^{Layers} \sum_{b=1}^{BlkN(l)} (1+ W_l)|DS_l - S_b| \qquad (3.9)$$

where,

Layers is the number of layers;

BlkN(l) is the number of cutblocks layer l;

DS_l is the desired cut block size of layer l;

S_b is the size of cut block b; and

W_l is the weight of layer l (the range is from 0.0 to 1.0 and the default value is 0).

Figure 3.11 shows that penalty is 0 when the actual cut block size S_b equals the desired size DS_l. The penalty increases when the actual cut block size S_b deviates from DS_l.

3.3.2.5 Profit, Road Construction, Logging and Transportation Costs

The road construction and transportation costs per cubic metre are incorporated in the objective function. Costs are most important in the short-term, so the logging, road construction and transportation costs are only applied in the first rotation.

Total value is calculated by equation 3.10; the road construction and transportation cost is calculated in equation 3.11; and the profit is calculated from equation 3.12.

$$TValue = \sum_{p=1}^{Periods} \sum_{b=1}^{Polys} Vol_{pb} * SP_{pb} \tag{3.10}$$

$$Cost = \sum_{p=1}^{Periods} \sum_{b=1}^{Polys(p)} (RoadC_{pb} + TranC_{pb} + LogC_{pb} + OtherC_{pb}) \tag{3.11}$$

$$P = TValue - Cost \tag{3.12}$$

where,

Polys(p) is the number of polygons harvested at period p ;

Periods is number of cost control periods (<one rotation).

TValue is the timber value produced in the cost control periods,

Vol_{pb} is the timber volume produced from polygon b in period p;

Cost is the total road construction and transportation cost;

$RoadC_{pb}$ is road construction cost of block b in period p;

$TranC_{pb}$ is transportation cost of block b in period p;

$LogC_{pb}$ is the logging cost of block b in period p;

$OtherC_{pb}$ is other timber production cost from polygon b in period p;

P is the total profit (timber value – cost); and

SP_{pb} is the timber price of polygon b in period p ($\$/m^3$).

3.3.2.6 Objective Function

The objective function (equation 3.13) is:

Maximize

$$F = V/Vo - (w_1X/Xo + w_2Y/Yo + w_3Z/Zo + w_4S/So) + w_5P/Po \quad (3.13)$$

Where,

F is the total objective function value (equation 3.13);

V is the total timber production;

X is the total patch size distribution penalty (equation 3.1);

Y is the total age class structure penalty (equation 3.3);

Z is the total volume flow penalty (equation 3.6);

S is the cut block size penalty (equation 3.8);

P is the profit (equation 3.12);

Vo, Xo, Yo, Zo, So and Po are initial values (at iteration 1) of V, X, Y, Z, S and P, respectively. V, X, Y, Z, S, and P are not directly comparable because they have different measuring units. To make them comparable, the objective function value at iteration N is the sum of the ratios between the values at iteration N and the initial values (at iteration 1), respectively. w_1, w_2, w_3, w_4 and w_5 are weighted

factors for each objective, respectively. The default values of w_1, w_2, w_3, w_4 and w_5 are 1. Penalties in the objective function are additive. An alternative would be more effective at detecting large deviations within individual planning periods.

3.3.3 Solution Transformation

The transformation operation uses the following 3-step procedure:

Step 1. Randomly select a polygon,

Step 2. Randomly select a cut year for the polygon. This change may affect subsequent cuts of the polygon, which may require adjustments to maintain minimum harvest ages.

Step 3. Evaluate the new solution and decide whether it is to be accepted or rejected. The acceptance probability equation used is:

$$P = 1 \qquad \text{for } E_2 \geq E_1,$$

$$P = e^{\left(\frac{(E2 - E1)/E1}{kT}\right)} \qquad \text{for } E_2 < E_1 \qquad (3.14)$$

where,

e = 2.71828 (constant);

P is the acceptance probability;

k is a constant (Boltzmann's constant);

T is temperature;

E_1 is the objective function value of the old solution; and

E_2 is the objective function value of the new solution.

At the beginning iterations, k and T should make P large enough so that the process can escape the local optimum. Gradually the acceptance probability P is reduced to zero as the iterations increase in order to freeze the solution (Figure 3.12).

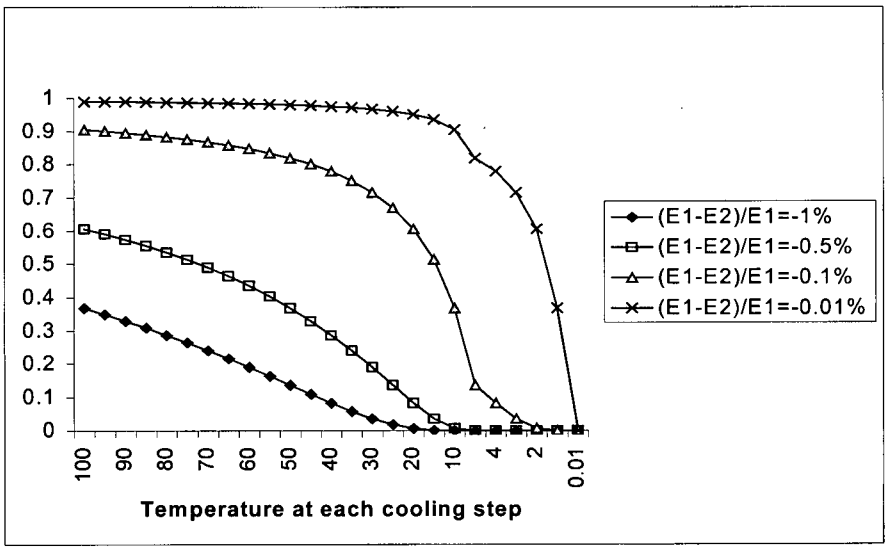


Figure 3.12 - Sample acceptance probabilities based on equation 3.14.

The solution transformation process is illustrated with the following example (Table 3.4 and Table 3.5):

Table 3.4 - A sample solution before transformation.

Polygon	Number of Cut Times	First Cut Year	Second Cut Year	Third Cut Year	Fourth Cut Year	...
1	2	2000	2200			
2	3	2035	2155	2255		
3	2	2055	2345			
4	4	2010	2100	2190	2210	
5	3	2060	2170	2295		
...	...	...				

Step 1. Randomly select a polygon A, for this example, let A = 2.

Step 2. Randomly select a cut B of polygon A among {1, 2, 3}, let B = 2.

Transform the solution. In this step, randomly change the cut year (2155) of B of polygon A, let the new cut year be 2175. The subsequent cut year has to be checked to be sure that the minimum harvest age is satisfied. If not, a new cut year has to be selected. All subsequent cut years are checked in the same way. If the last cut year of polygon A is changed, it is necessary to check if more cuts are possible during the planning horizon. In this example, the minimum harvest age is 70 and 2255-2175 = 80 > 70, so it is not necessary to change the third cut year 2255 (Table 3.5).

Table 3.5 - Sample solution after transformation.

Polygon No.	Cut Times	First Cut Year	Second Cut Year	Third Cut Year	Fourth Cut Year	...
1	2	2000	2200			
2	3	2035	**2175**	2255		
3	2	2055	2345			
4	4	2010	2100	2190	2210	
5	3	2060	2170	2295		
...	...	...				

Step 3. Evaluate the new solution by calculating the timber flows, timber value, production costs, and penalties, and decide whether to accept or reject the transition. If the new solution is equal or better than the previous one, accept the new one immediately; otherwise base acceptance on equation 3.14. The poorer the solution is, the lower is the acceptance probability. The high iteration numbers also have a low acceptance probability (Figure 3.12).

The transformation process will be repeated (step 1 – 3) until a maximum iteration is reached, or no acceptable transitions occur in a specified number of tries.

3.3.4 Procedures of Simulated Annealing for TFBS

Figure 3.13 shows the procedure for solution initialization. There are five steps in this procedure:

Step 1. build a list of available polygons for harvesting according to "hard constraints" such as minimum harvest age; stop if no polygons are in the list.

Step 2. randomly select a polygon "x" from the list;

Step 3. identify next harvest year range "R" of the selected polygon (the harvest year range is defined according to biological minimum harvest age and maximum harvest age);

Step 4. randomly identify a harvest year "y" in the range R of polygon "x"; and

Step 5. if "y" is inside the planning horizon, accept the cut and go to step 3, else go to step 1.

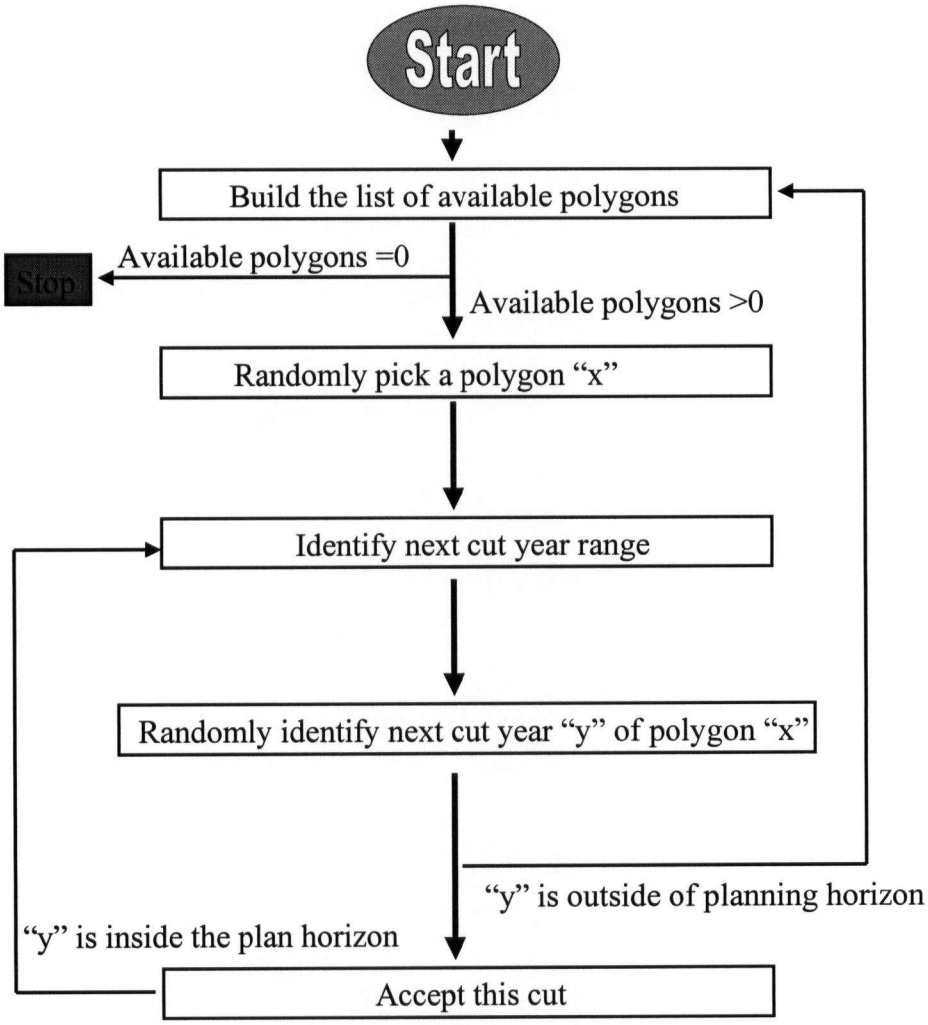


Figure 3.13 - Procedure for solution initialization.

The simulated annealing procedures used in this thesis are summarized in Figure 3.14. After the solution is initialized (Figure 3.13), randomly select and change the harvesting year. The new solution is evaluated. The probability of accepting the new solution is calculated by equation 3.14.

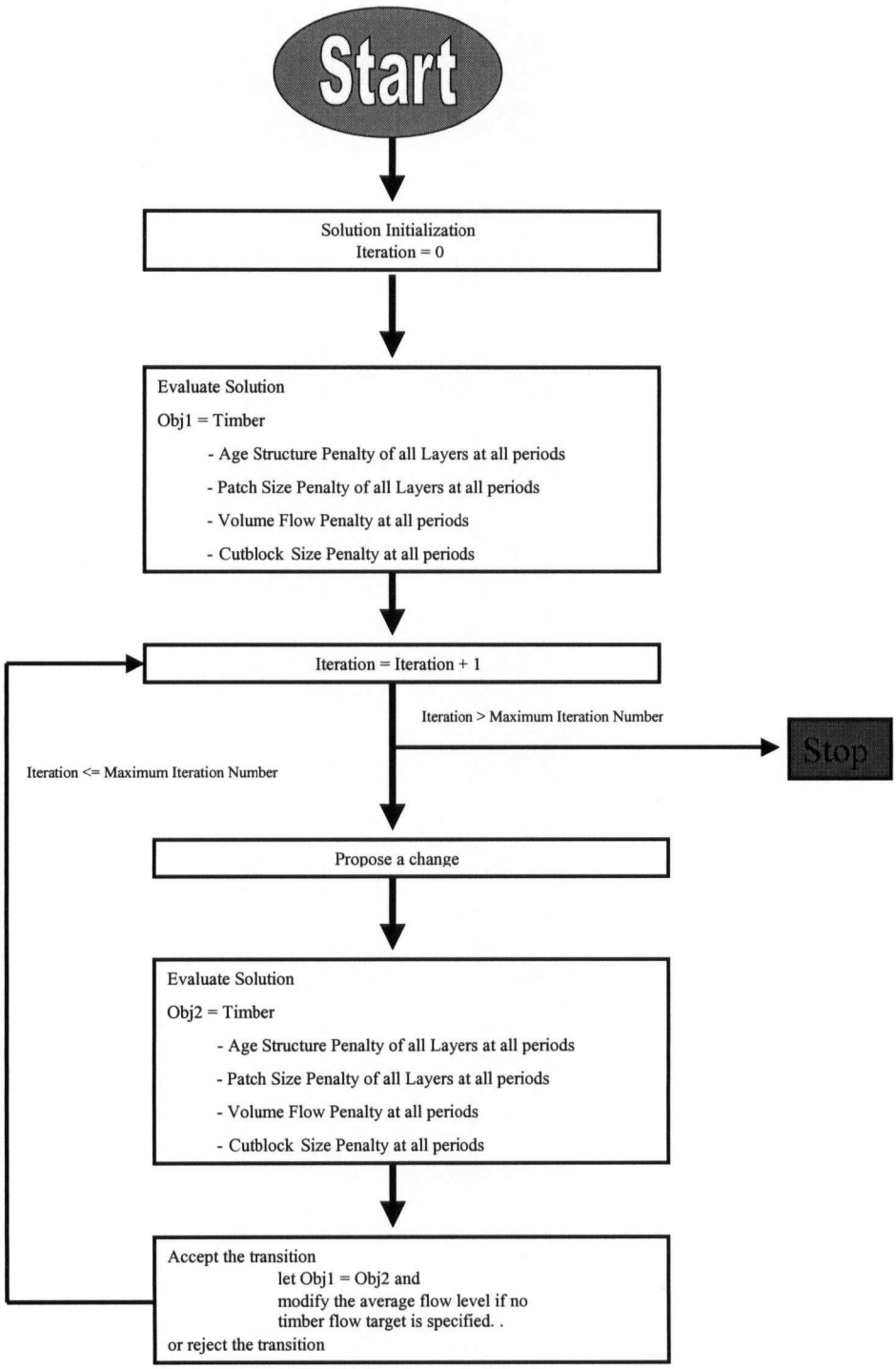


Figure 3.14- General procedure for the simulated annealing algorithm.

Chapter 4

Model Testing

In this chapter, each function of the FSOS is tested on a simple data set. The sample data set has 400 square polygons and each polygon is 10 hectares in size. The following scenarios (Table 4.1) are tested:

1) The first scenario, S4.1, is used to test sensitivity of the solutions to different starting points and cooling rates. Scenario S4.1 includes block size control, total timber production, and periodic timber flow control. The best cooling scheme was identified according to the performances of all the runs in scenario S4.1, and this cooling scheme is used for all the following scenarios.
2) Scenarios S4.2.1.1, S4.2.1.2, and S4.2.1.3 test the sensitivity of road construction cost on block building and scheduling.
3) Scenarios S4.2.2.1, S4.2.2.2, and S4.2.2.3 test the sensitivity of transportation cost on block building and scheduling.
4) Scenarios S4.3.1, S4.3.2, S4.3.3 and S4.3.4 test the sensitivity of age structure and patch size distributions under different initial inventories (forest states).
5) Scenarios S4.4.1.1, S4.4.1.2, S4.4.1.3, S4.4.2.1, S4.4.2.2, and S4.4.2.3 are used to compare volume flows, age and patch size distribution results to those generated by a time step simulation model, ATLAS.

6) Scenarios S4.5.1, S4.5.2 and S4.5.3 test the sensitivity of natural disturbance on timber flows and patch patterns.

Table 4.1 - Testing scenarios.

Scenarios	Objectives	Block Size	Total Timber Volume	Timber Flow	Timber Value	Costs	Age Structure	Patch Size Distribution
S4.1	Identify proper cooling schemes. Test block size controls.	Yes	Yes	Yes	No	No	No	No
S4.2.1.1 S4.2.1.2 S4.2.1.3	Test road cost Impacts on block locations.	Yes	Yes	Yes	Yes	Yes	No	No
S4.2.2.1 S4.2.2.2 S4.2.2.3	Test transportation cost impacts on block locations.	Yes	Yes	Yes	Yes	Yes	No	No
S4.3.1 S4.3.2 S4.3.3 S4.2.4	Test age structure, patch size distribution controls.	Yes	Yes	Yes	No	Yes	Yes	Yes
S4.4.1 S4.4.2 S4.4.3	Test natural disturbance impacts on timber flows and patches.	Yes	Yes	Yes	No	No	Yes	Yes
ATLAS Runs: S4.5.1.1 S4.5.1.2 S4.5.1.3 FSOS Runs: S4.5.2.1 S4.5.2.2 S4.5.2.3	Compare time-step simulation model Atlas and FSOS.	Yes	Yes	Yes	No	No	Yes	Yes
Plan horizon (Years)		200	200	200	10	10	200	200

Timber value and costs are applied for 10 years only, because: 1) timber value changes rapidly with market fluctuations and utilization levels, 2)

production costs change when technology and harvesting systems change, and 3) roads are rarely laid out beyond 10 years. The planning horizon for all other objectives is 200 years.

4.1 Basic Scenario (Scenario S4.1)

The objectives of the basic scenario are to test if the model can build desired block sizes and to identify the best cooling schemes. To simplify the problem, only timber flow and block size controls are applied. Two layers are defined in Figure 4.1, and different target block sizes are applied to each layer. The following assumptions are made: 1) all polygons are 160 years old, 2) all polygons use the same volume-age curves, and 3) adjacent blocks are not allowed in the same period. Adjacent blocks are defined as blocks sharing a common point.

To test if blocks are built properly and if different starting points (initial solutions) affect model performance, four runs were conducted with the same parameters but with different starting points. The target block size for layer 1 is greater than or equal to 10 ha and less than 40 ha, while for layer 2 it is greater than or equal to 20 ha and less than or equal to 60 ha.

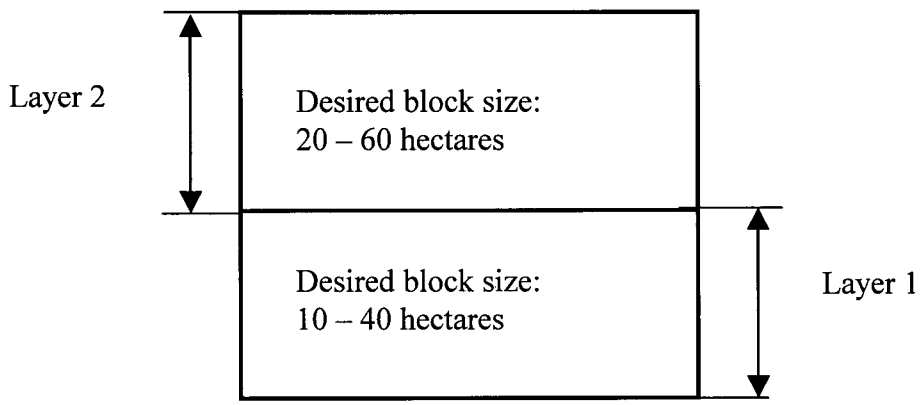


Figure 4.1 - Two-layer block size targets for scenario S4.1.

Figure 4.2 shows the blocks built during the first 4 periods of each run. The block patterns are different for each run, but almost all the blocks in the four runs meet the desired sizes. Only one block (circled in run 2, Figure 4.2) in layer 2 is 10 ha which is less than the minimum desired size of 20 ha.

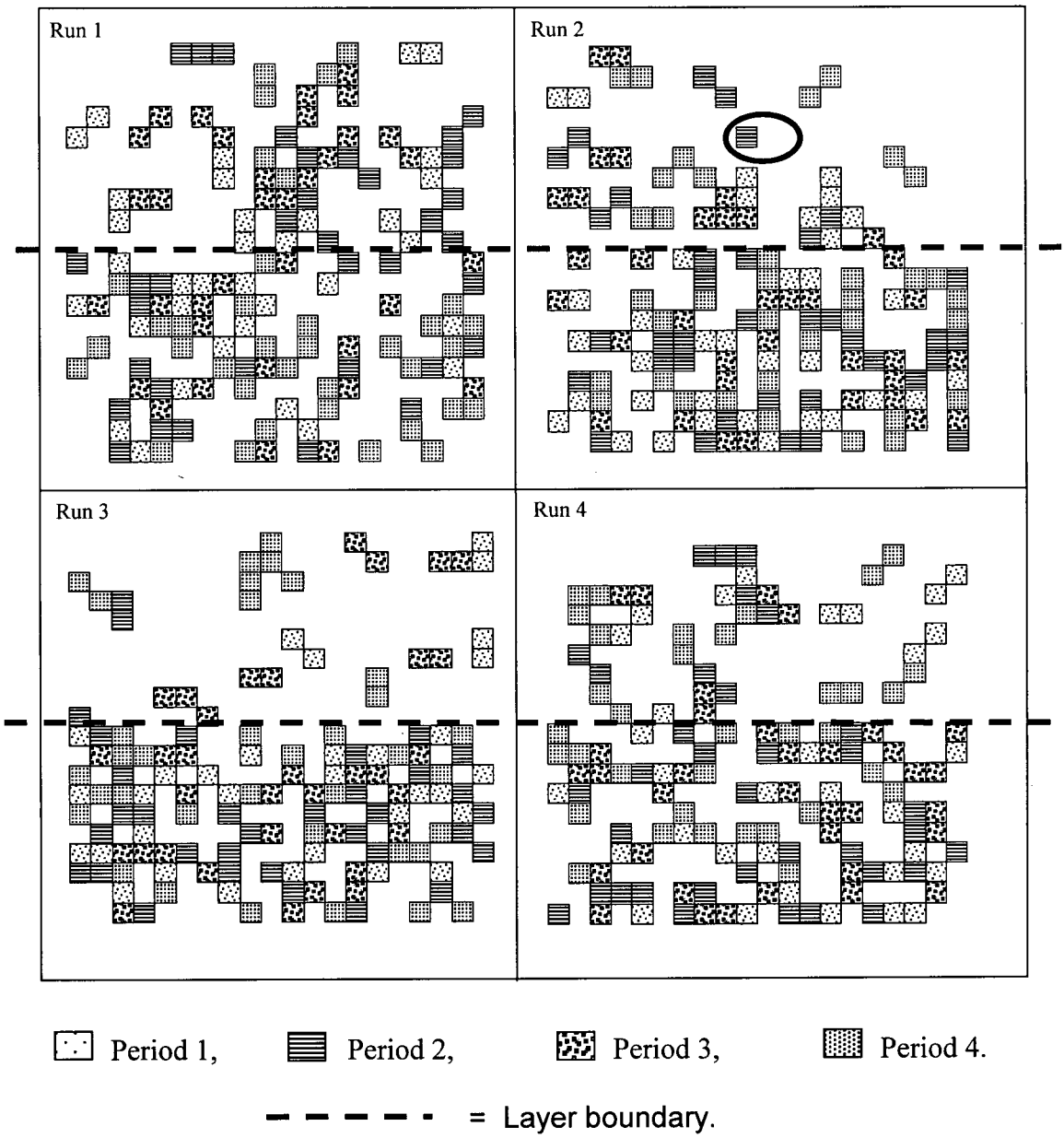


Figure 4.2 - Cut blocks built during the first four periods for scenario S4.1.

Figure 4.3 plots the simulated annealing objective function values for each run. These values are similar for different starting points (all other parameters held constant). This is expected because there are numerous good solutions for this problem.

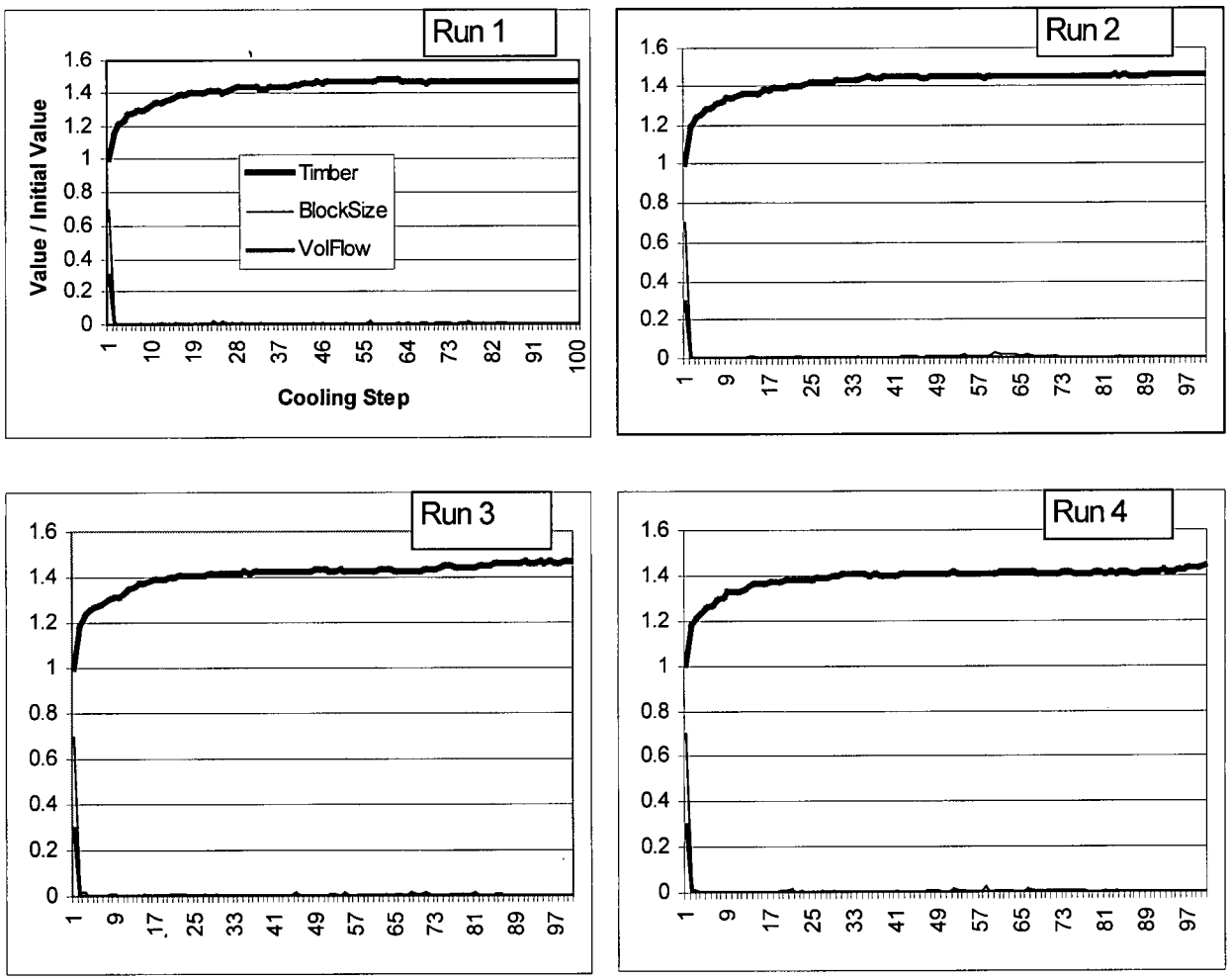


Figure 4.3 - SA objective function values for each run (scenario S4.1).

Figure 4.4 shows the timber flows for each run. The timber flows are almost identical for the different starting points, although the harvesting patterns are different (Figure 4.2). This result was expected because there are numerous

good solutions for this problem. The runs indicate that different starting points affect the harvest patterns but have little effect on volume flows and total solution value.

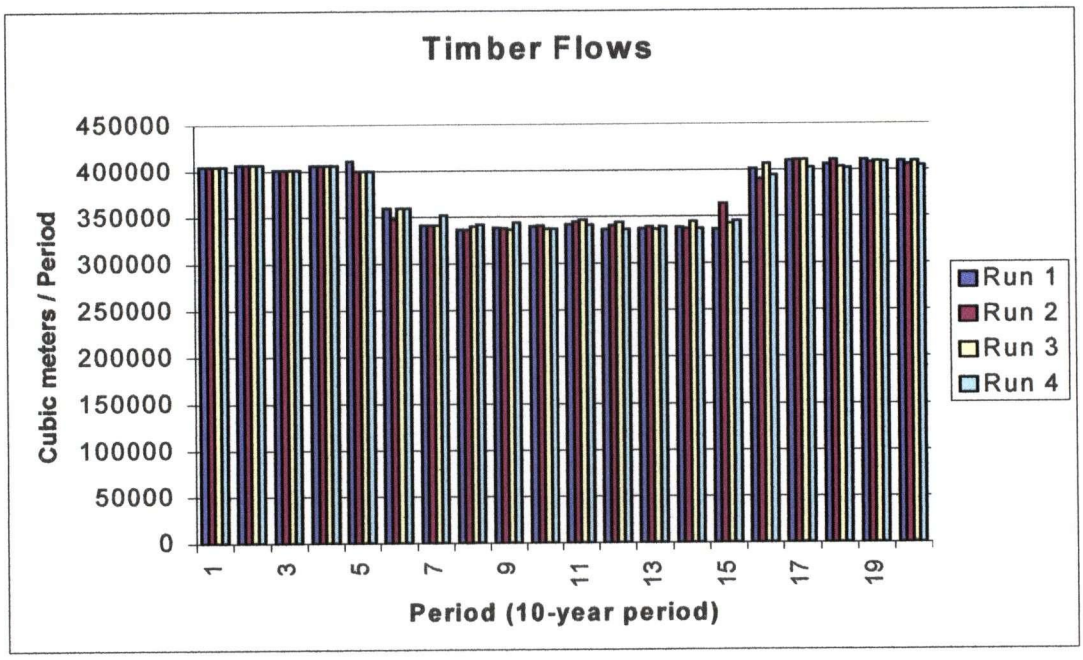


Figure 4.4 - Timber flows of the four runs for scenario S4.1.

Sensitivities of Timber Flows to Cooling Schemes

The performance of SA for maximizing timber volume was tested using 7 different cooling rates in scenario S4.1. Hill climbing, which can be thought of as the fast cooling scheme, is the least effective while SA with C=0.01 consistently performs the best. All solutions found by SA are between 96% and 100% of the best solution found by SA (Figure 4.5 and Table 4.2). All runs met targets for block size and volume flows within a 5% tolerance. The runs are summarized in

Table 4.2. Table 4.3 shows the temporal performances of SA when the cooling rate is 0.01. Timber flow is sensitive to the cooling scheme, which suggests a number of runs are necessary to identify the best cooling scheme.

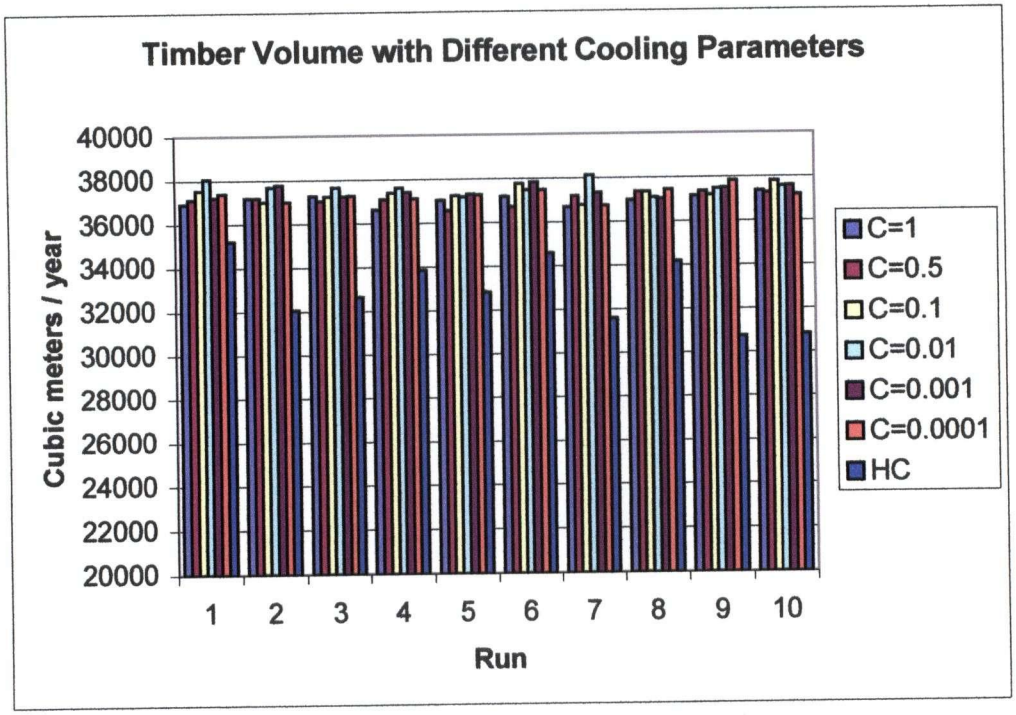


Figure 4.5 - Timber volume per year for 7 different cooling schemes (10 runs each).

Table 4.2 - Summary of timber flows for 10 runs with 7 different cooling schemes for scenario S4.1.

Cooling Control Parameters	C=1	C=0.1	C=0.5	C=0.01	C=0.001	C=0.0001	Hill Climbing
Average (m3/year) (% of Maximum)	37,041 (97.11%)	37,095 (97.27%)	37,335 (97.88%)	37,597 (98.57%)	37,427 (98.13%)	37,283 (97.75%)	32,869 (86.17%)
Maximum (m3/year) (% of Maximum)	37,358 (97.94%)	37,370 (97.98%)	37,808 (99.12%)	38,142 (100%)	37,840 (99.21%)	37,838 (99.20%)	35,226 (92.35%)
Minimum (m3/year) (% of Maximum)	36,620 (96.01%)	36,577 (95.90%)	36,772 (96.41%)	37,104 (97.28%)	37,026 (97.07%)	36,749 (96.35%)	30,768 (80.67%)

Table 4.3 - Temporal performance of SA with C=0.01 for scenario S4.1.

Iterations	Temperature With cooling control parameter c = 0.01	Time(Minutes) with Pentium 266 98 MB RAM	Total Volume (percent of maximum SA solution found)	Total Objective Function Value	Timber Volume Divided by Initial Timber Volume	Block Size Penalty Divided by Initial Block Penalty	Volume Flow Penalty Divided by Initial Volume Flow Penalty
5,000	100	0.5	5,093,035 (67.6%)	0.003	1.001	0.698	0.3
10,000	70	0.93	6,507,719 (86.4%)	1.278	1.281	0.002	0
15,000	40	1.45	6,796,042 (90.2%)	1.336	1.333	0	0
20,000	20	1.91	7,027,543 (93.3%)	1.382	1.382	0	0
25,000	10	2.40	7,140,005 (94.8%)	1.404	1.402	0	0
30,000	9	2.90	7,145,801 (94.8%)	1.403	1.405	0.002	0
35,000	8	3.42	7,291,247 (96.8%)	1.431	1.432	0.002	0
40,000	7	3.89	7,281,231 (96.6%)	1.43	1.432	0.001	0
45,000	6	4.41	7,338,836 (97.4%)	1.441	1.441	0.001	0
50,000	5	4.93	7,434,878 (98.7%)	1.456	1.46	0.006	0
55,000	4	5.30	7,472,150 (99.2%)	1.457	1.468	0.012	0
60,000	3	5.89	7,501,771 (99.6%)	1.455	1.473	0.019	0
65,000	2	6.39	7,533,876 (100%)	1.477	1.479	0.004	0
70,000	1	6.86	7,500,991 (99.6%)	1.475	1.474	0	0
75,000	0.5	7.32	7,448,303 (98.9%)	1.452	1.465	0.013	0
80,000	0.1	7.80	7,471,136 (99.2%)	1.46	1.466	0.009	0
85,000	0.05	8.30	7,466,438 (99.1%)	1.463	1.466	0.005	0
90,000	0.01	8.78	7,472,592 (99.2%)	1.464	1.469	0.005	0
95,000	0.001	9.10	7,474,897 (99.2%)	1.47	1.468	0	0
100,000	0.0001	9.50	7,475,097 (99.2%)	1.47	1.468	0	0

4.2 Testing Cost Objectives

In this section, cost control functions are used to test the sensitivity of block locations and schedules to costs. Costs include logging costs, transportation costs, road construction costs and other costs. Other costs ($/m^3) include administration, stumpage, and supervision.

To clearly demonstrate how the costs affect block locations, one layer is used. The same initial forest state as scenario S4.1 (all polygons are 160 years old) is used. Section 4.2.1 tests the sensitivity of block locations to road construction costs, and section 4.2.2 tests the sensitivity of block locations to transportation costs. The blocks must be 10 to 20 hectares in size, and the fluctuation of timber flows within 10%. The cost and profit flows are applied for the first 10 years only, while all other objectives are applied for 210 years.

4.2.1. The Effects of Road Construction Cost on Blocking and Scheduling

In Table 4.4, the three scenarios differ only in the road construction cost ($/Km). The remaining parameters are the same as scenario S4.1.

Table 4.4 - Parameters for scenarios S4.2.1.1, S4.2.1.2, and S4.2.1.3.

Scenario	S4.2.1.1	S4.2.1.2	S4.2.1.3
Timber value ($/m^3)	200	200	200
Road construction cost for all roads ($/km)	**100,000**	**10,000**	**1,000**
Transportation cost ($/m^3/km)	0.1	0.1	0.1
Logging cost ($/m^3)	18	18	18
Other cost ($/m^3)	39	39	39

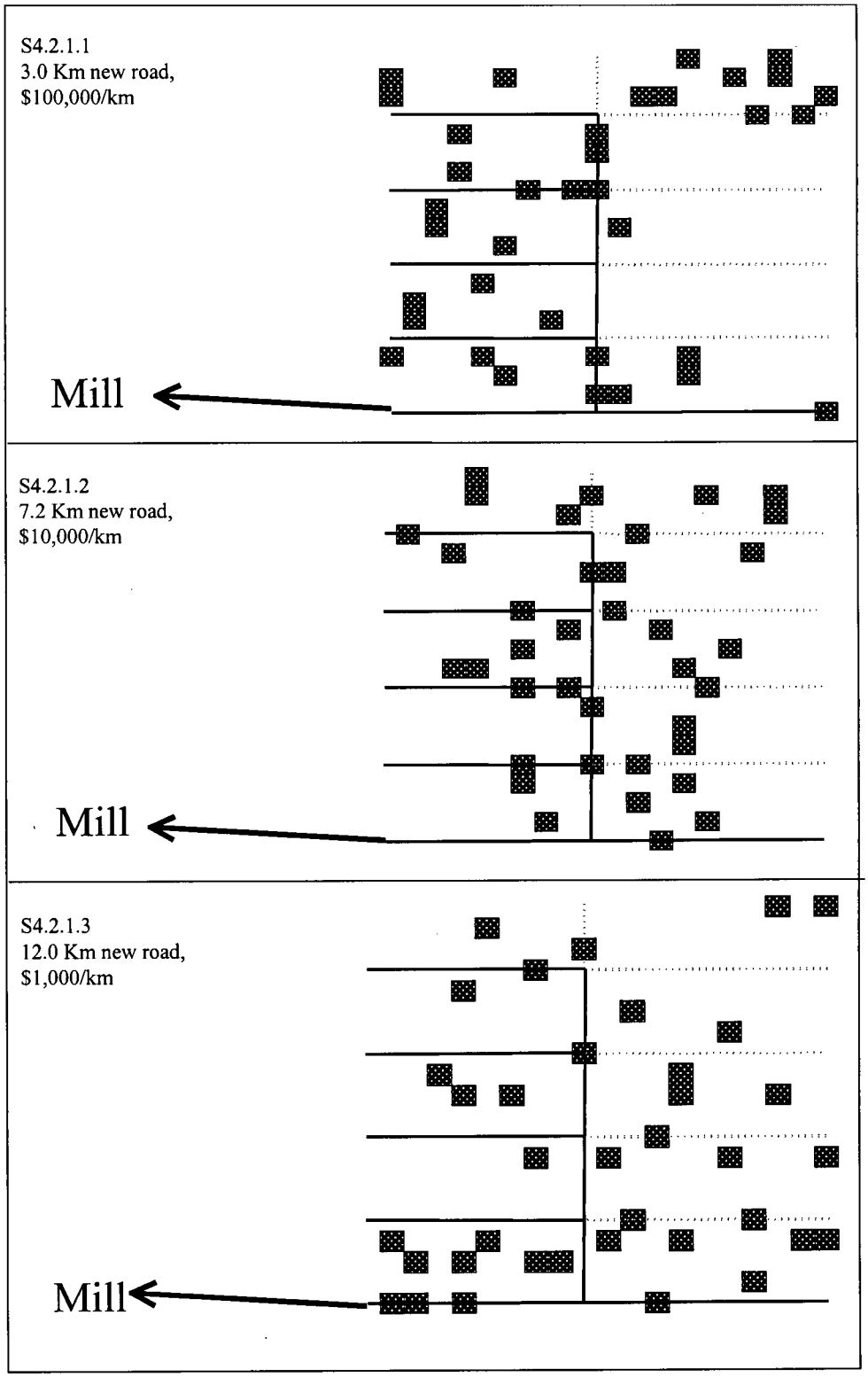


Figure 4.6 - Cut blocks for first ten years with different road construction costs ($/km) for scenario S4.2.1.1, S4.2.1.2, and S4.2.1.3. (solid lines are existing roads, and dotted lines are proposed roads).

Figure 4.6 shows harvest blocks and road systems during the first 10 years. All blocks are in the target size range (10-20 hectares). In scenario 4.2.1.1, most of the blocks are allocated around existing roads, and three kilometers of new road are needed. In scenario 4.2.1.2, when the road construction cost per kilometer is reduced to $10,000/km, more blocks are allocated in areas without existing roads, and 7.2 kilometers of new roads are required. In scenario 4.2.1.3, the road construction cost per kilometer is reduced again to $1000/km, and more blocks are allocated in areas without roads (12 kilometers of new roads, Table 4.5). The total logging and transportation costs are about 23 million dollars, of which the road construction costs are less than 0.3 million dollars. In this example, the road construction cost is only about 1.5% of the total cost, so the results are not very sensitive to road construction costs. However, block patters do indicate the expected trends relative to road construction costs.

Table 4.5 - Summary of scenarios S4.2.1.1, S4.2.1.2, and S4.2.1.3.

Scenario	S4.2.1.1	S4.2.1.2	S4.2.1.3
Timber volume flows (m^3)	383,573	394,228	394,228
Timber value ($)	76,714,560	78,845,520	78,845,520
New road (km)	**3.0**	**7.2**	**12.0**
Road construction cost for all roads ($)	297,489	71,596	12,031
Transportation cost ($)	486,811	481,027	432,896
Logging cost ($)	6,904,313	7,096,099	7,096,099
Other cost ($)	14,959,335	15,374,872	15,374,872
Total cost ($)	22,647;947	23,023,594	22,915,898
Profit ($)	54,066,613	55,821,926	55,929,622

Figure 4.7 shows the timber flows for the three scenarios. The timber flows are similar even though the block patterns are different. There appears to be many good solutions for these problems. The total profit and cost for the three scenarios are similar because the road construction cost is only 1.5% of the total cost; as a result, road construction cost has little impact on the total cost and profit.

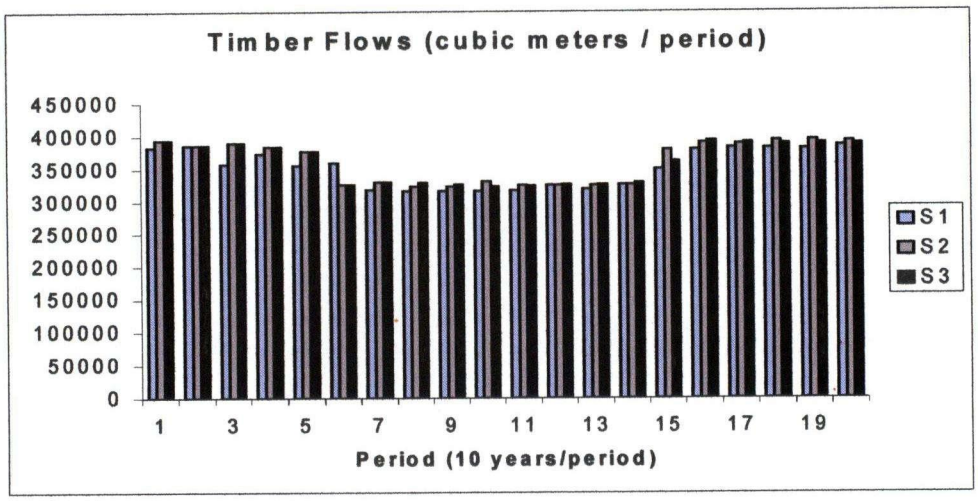


Figure 4.7 - Timber flows for scenarios S4.2.1.1, S4.2.1.2, and S4.2.1.3.

4.2.2. The Effect of Transportation Costs on Blocking and Scheduling

The three scenarios in Table 4.6 differ only in transportation cost ($/m^3/km).

Table 4.6 - Parameters for scenarios S4.2.2.1, S4.2.2.2, and S4.2.2.3.

Scenario	S4.2.2.1	S4.2.2.2	S4.2.2.3
Timber value ($/m^3)	200	200	200
Road construction cost for all roads ($/km)	100,000	100,000	100,000
Transportation cost ($/m^3/km)	**0.1**	**1**	**10**
Logging cost ($/m^3)	18	18	18
Other cost ($/m^3)	39	39	39

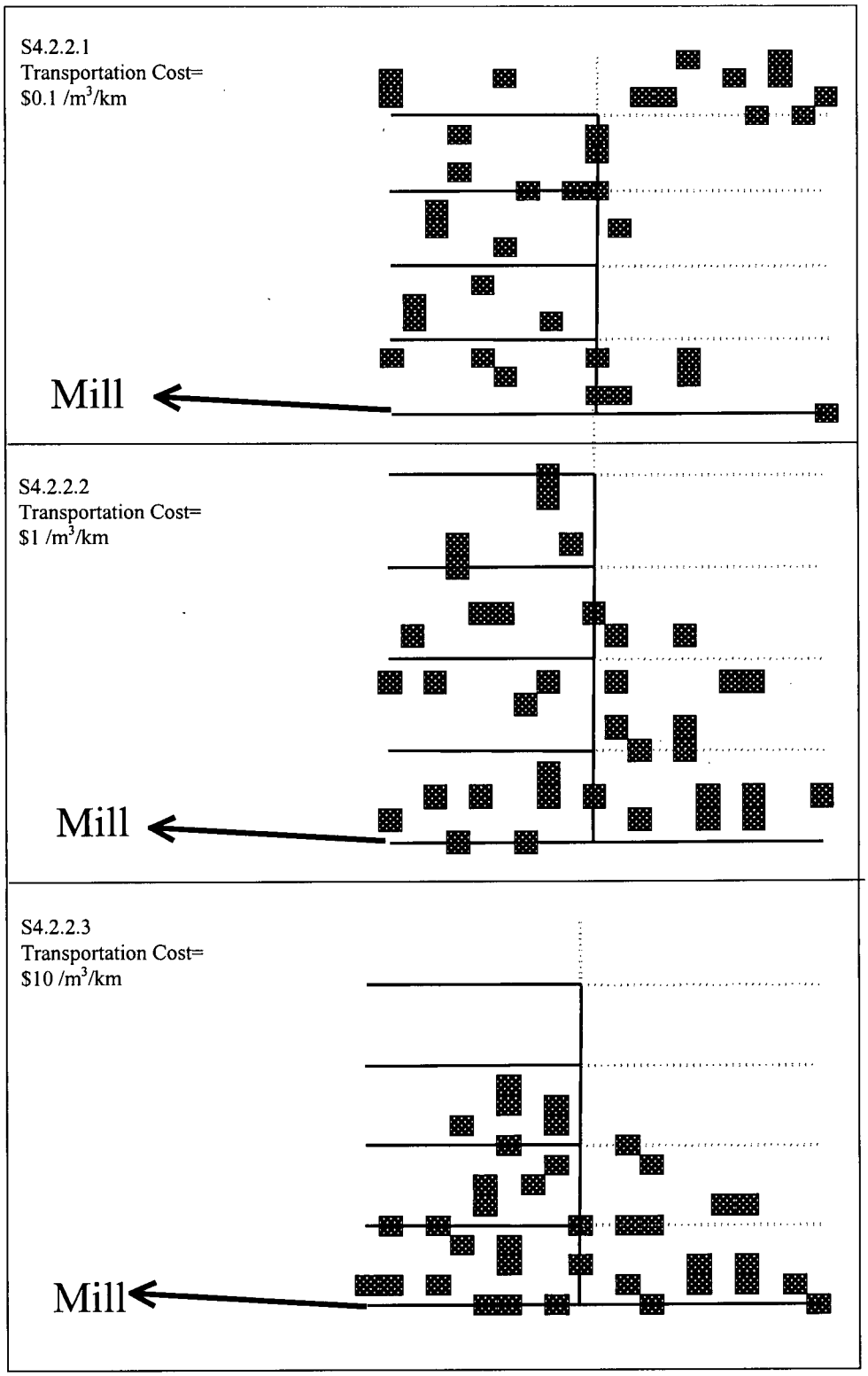


Figure 4.8 - Cut blocks built during first ten years with different transportation costs ($/m^3/km) for scenarios S4.2.1.1, S4.2.1.2, and S4.2.1.3. (solid lines are existing roads and dotted lines are proposed roads).

Figure 4.8 shows the block patterns created during the first 10 years of each scenario. More blocks are allocated closer to the mill when the transportation cost ($/m^3/km) increases. Table 4.7 summarizes the costs for each scenario.

Table 4.7 - Summary of scenarios S4.2.2.1, S4.2.2.2, and S4.2.2.3.

Scenario	S4.2.2.1	S4.2.2.2	S4.2.2.3
Timber volume flows (m^3/year)	383,573	383,573	394,228
Timber value ($/m^3)	76,714,560	76,714,560	78,845,520
New roads (km)	3.0	3.4	2.8
Road construction cost for all roads ($)	297,489	342,178	278,978
Transportation cost ($)	**486,811**	**4,021,972**	**37,826,212**
Logging cost for ($)	6,904,313	6,904,313	7,096,099
Other cost ($)	14,959,335	14,959,335	15,374,872
Total cost ($)	22,647,947	26,227,797	60,576,161
Profit ($)	54,066,613	50,486,763	18,269,359

Figure 4.9 shows that the timber flows for all three scenarios are similar suggesting that there are numerous spatial solutions which result in good values. Scenario S4.2.2.3 with the most expensive transportation cost ($/km/m^3) has the lowest profit.

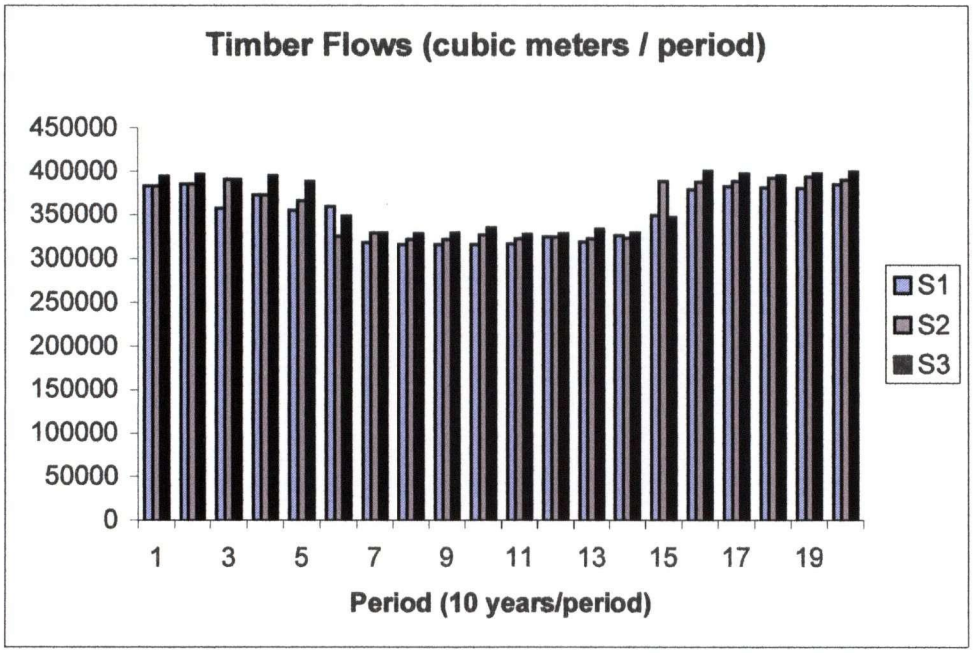


Figure 4.9 - Timber flows for scenarios S4.2.2.1, S4.2.2.2, and S4.2.2.3.

4.3 Age Structures and Patch Size Testing Using Different Initial States

To test if the model can build and maintain desired age structures and patch size distributions from different initial states, two layers (Figure 4.10) are used. The initial states (age and arrangements of stands) for the four scenarios are different (Table 4.8), but target age structures and patch size distributions for the four scenarios are the same (Figure 4.10). For both layers, the old (>100 years) stand age class target is a minimum target, the small (<40 ha) old patch target is a maximum target and the large (>=40 ha) old patch target is a minimum target for all scenarios. The tolerance for all age structure and patch targets is 10%. The layers differs only in the % area allocated to each patch target (30% v. 70%).

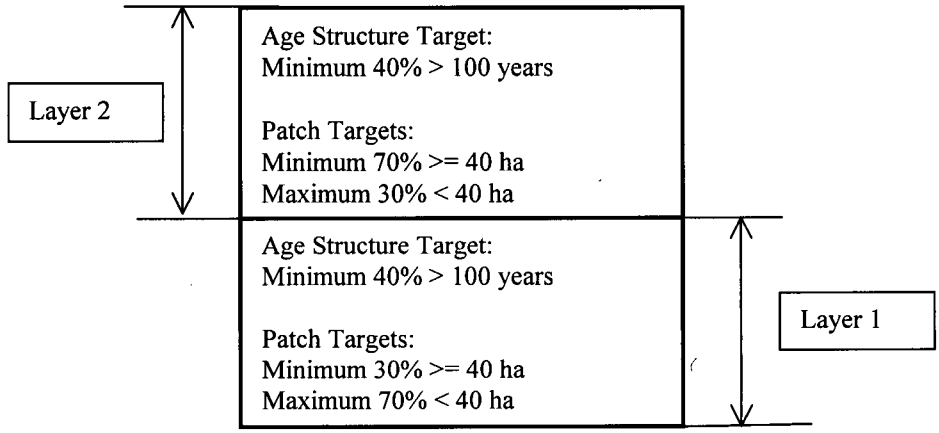


Figure 4.10 - Age and patch targets for scenarios S4.3.1, S4.3.2, S4.3.3, S4.3.4.

Table 4.8 - Initial states for scenarios S4.3.1, S4.3.2, S4.3.3, and S4.3.4.

Scenario	Initial ages for polygons
S4.3.1	160 years
S4.3.2	0 – 160 years (random)
S4.3.3	50 years
S4.3.4	0 - 50 years (random)

Results of Scenario S4.3.1

(All polygons are 160 years old in the initial forest)

Figure 4.11 and 4.12 show temporal changes in the age structures and patches in layer 1, respectively. The existing forest is already in the desired state, and the desired state is maintained within a 10% tolerance over the entire planning horizon. The current state of old stands in layer 1 is 100%, and this is gradually reduced to 38% over time. This desired state is maintained for the rest

of the planning horizon within the 10% tolerance. The current state of old patches in layer 1 is 100% in the larger size (>=40 hectares) category and is gradually divided into smaller (<40 hectares) patches as scheduling creates a transition towards the desired patch targets.

Figure 4.13 and 4.14 show temporal changes in the age structures and patches in layer 2. The existing forest is already in the desired state, and the desired state is maintained within a 10% tolerance over the entire planning horizon. The old stands in layer 2 currently cover 100% of the layer and are gradually reduced to 40% (within a 10% tolerance). The old patches in layer 2 are currently 100% in the larger size (>=40 hectares) and are gradually divided into smaller sizes (<40 hectares) as scheduling creates a transformation toward the target. The desired age structure and patch targets for both layers are achieved and maintained even though they have different targets.

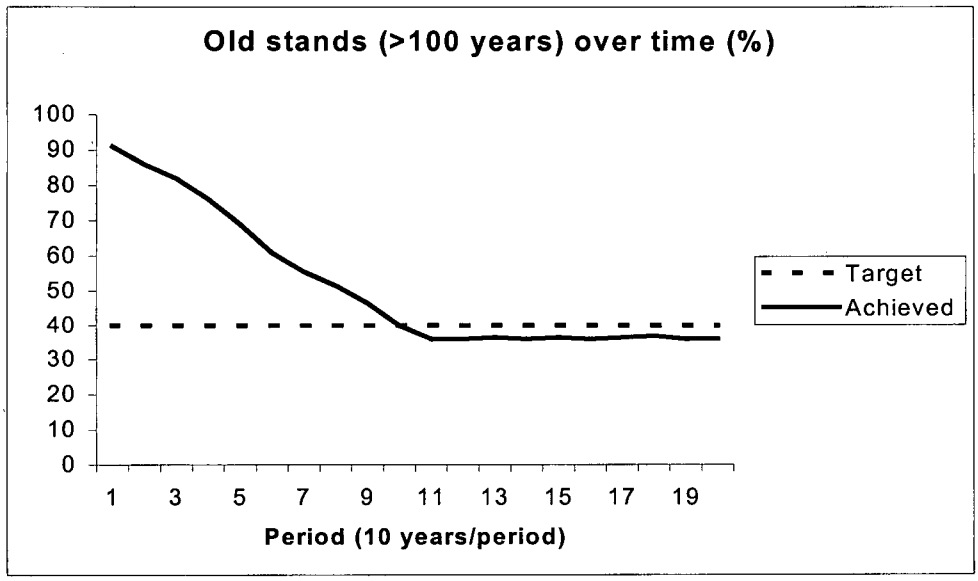


Figure 4.11 - Old (>100 years) stands in layer 1 for scenario S4.3.1
(All polygons are 160 years old at the start).

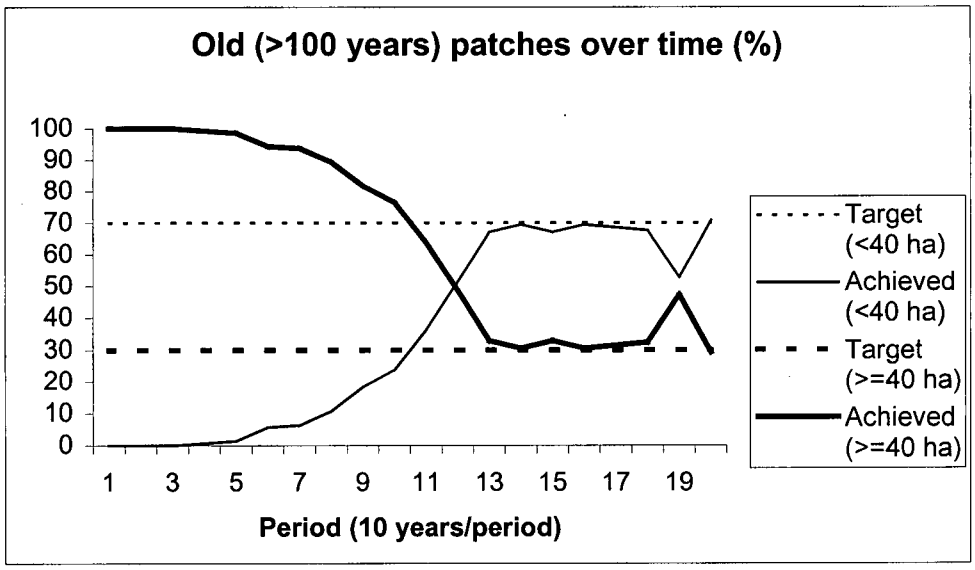


Figure 4.12 - Old (>100 years) patches in layer 1 for scenario S4.3.1
(All polygons are 160 years old at the start).

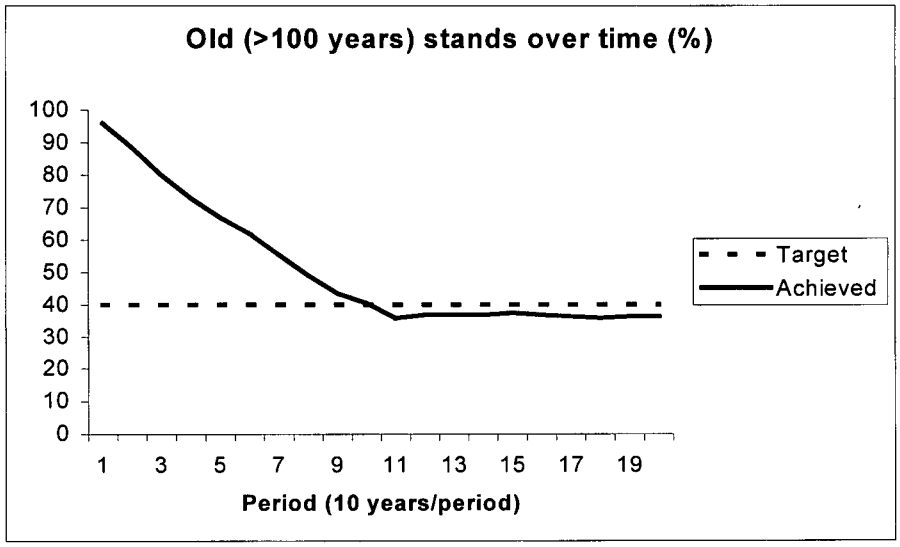


Figure 4.13 - Old (>100 years) stands in layer 2 for scenario S4.3.1
(All polygons are 160 years old at the start).

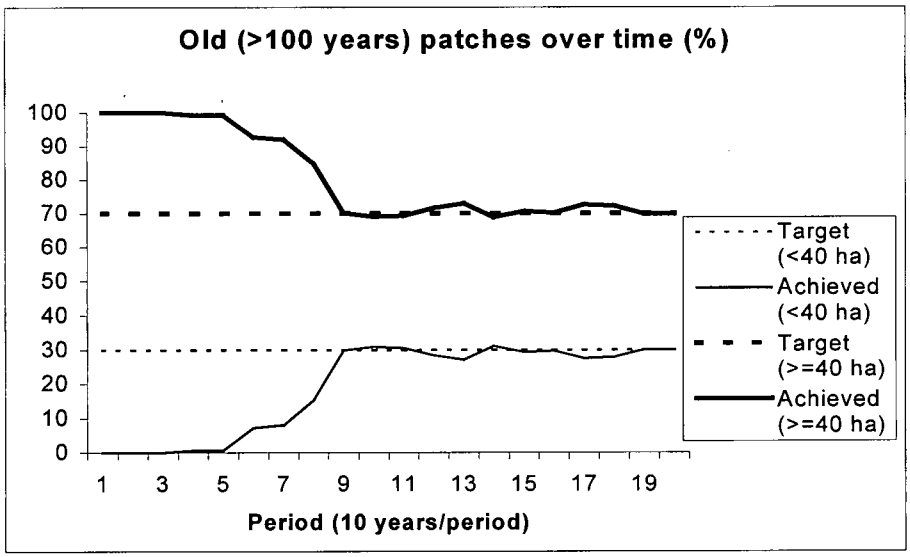


Figure 4.14 - Old (>100 years) patches in layer 2 scenario S4.3. 1
(All polygons are 160 years old at the start).

Figure 4.15 shows four snapshots of the old (>100 years) patches at years 2000, 2100, 2150 and 2200 (or years 0, 100, 150 and 200) for scenario S4.3.1. The existing forest is a 160-year old even age forest. The old stand and patch targets are met at the beginning and maintained for the entire planning horizon.

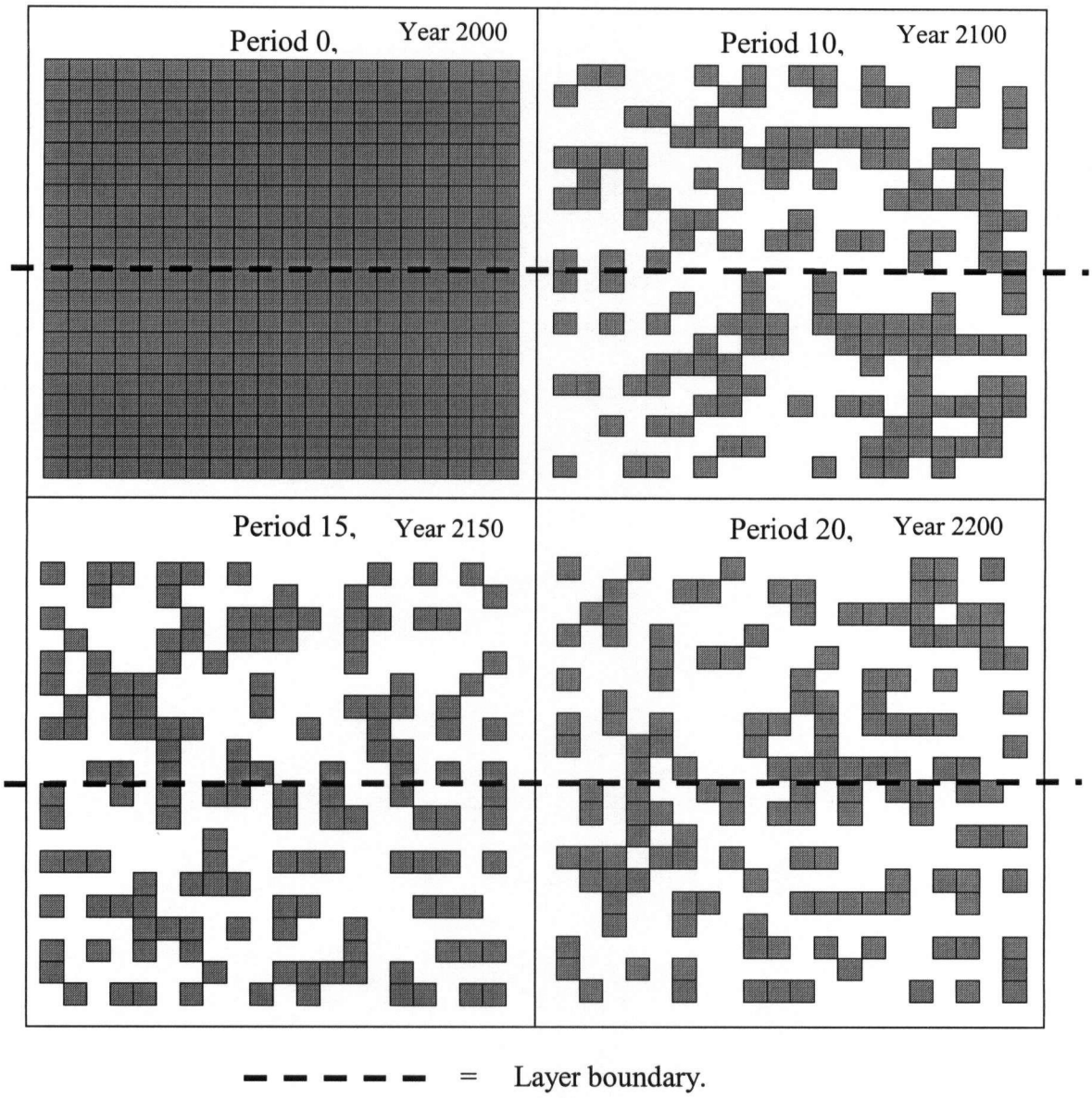


Figure 4.15 - Four snapshots of old (>100 years) stands for scenario S4.3.1 (All polygons are 160 years old at the start).

Results of Scenario S4.3.2

(Polygon ages are randomly 0–160 years in the initial forest)

Figures 4.16 and 4.17 illustrate the temporal changes of the old (>100 years) stands and patches for layer 1. The existing forest is very close to the desired state. This desired state is maintained within a 10% tolerance during the planning horizon. Figures 4.18 and 4.19 show the temporal changes of the old stands and patches in layer 2. The existing forest is already in the desired state, and the desired state is maintained with a 10% tolerance throughout the planning horizon.

Comparing Figures 4.17 and 4.19, the patch targets for both layer 1 and layer 2 are achieved even though the two layers have very different patch targets. The old large (>=40 hectares) patch target for layer 1 is 30% while the same target for layer 2 is 70%. The old small (<40 hectares) patch target for layer 1 is 70% while the equivalent target for layer 2 is 30% (Figure 4.10).

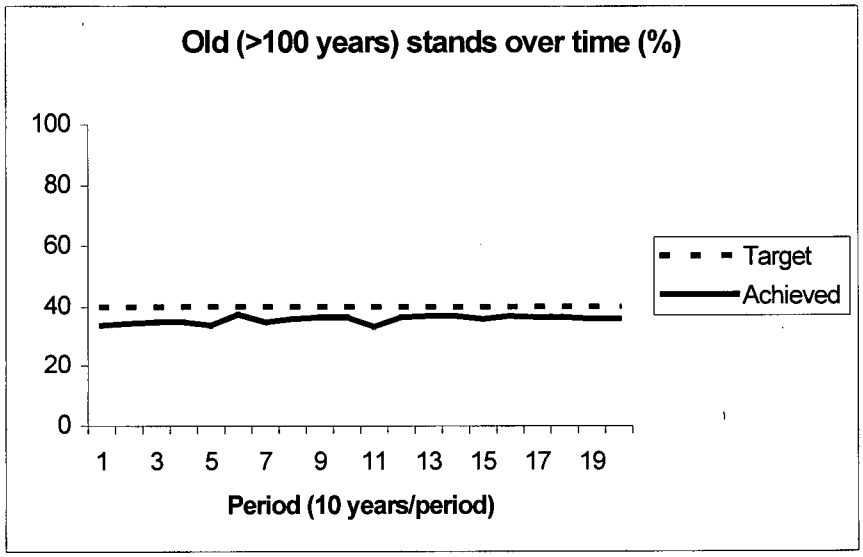


Figure 4.16 - Old (>100 years) stands in layer 1 for scenario S4.3.2 (Polygons are randomly 0-160 years at the start).

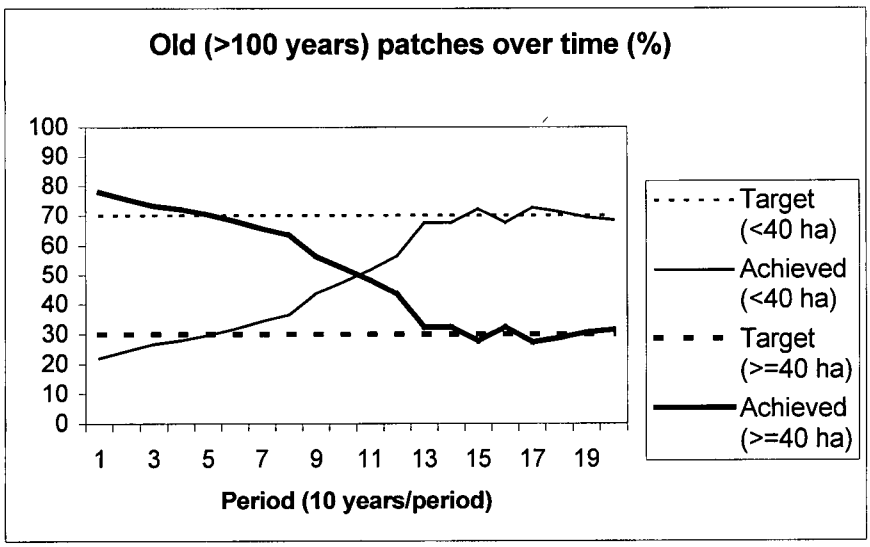


Figure 4.17 - Old (>100 years) patches in layer 1 for scenario S4.3.2 (Polygons are randomly 0-160 years at the start).

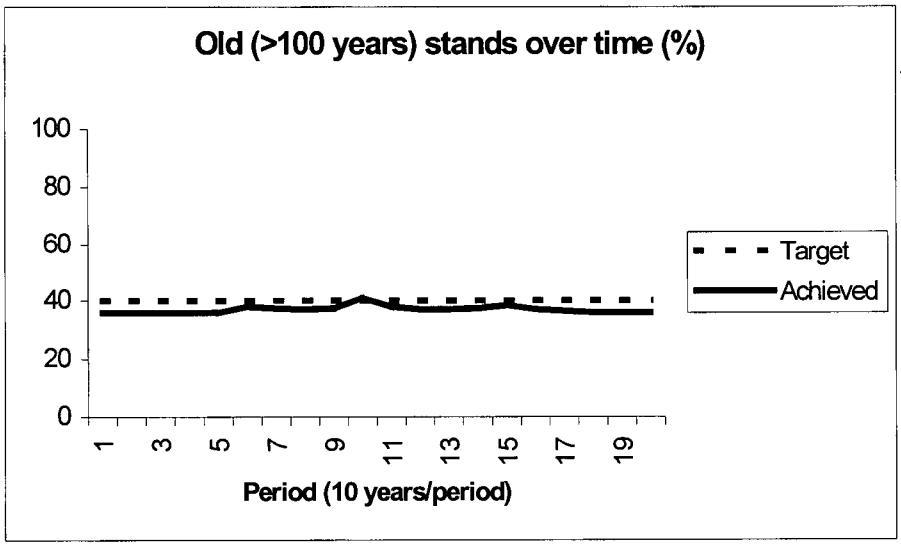


Figure 4.18 - Old (>100 years) stands in layer 2 for scenario S4.3.2 (Polygons are randomly 0-160 years at the start).

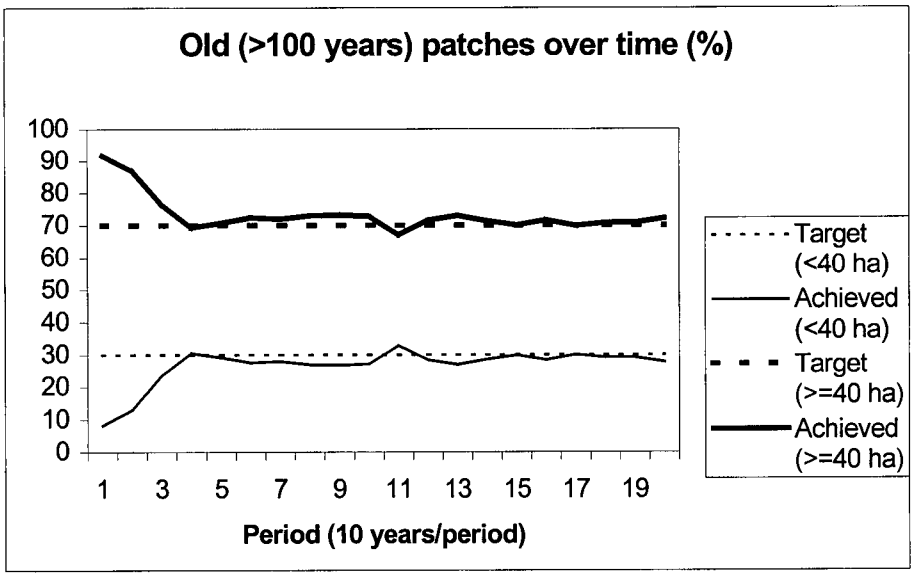


Figure 4.19 - Old (>100 years) patches in layer 2 for scenario S4.3.2 (Polygons are randomly 0-160 years at the start).

Figure 4.20 illustrates the four snapshots of the old (>100 years) patches at years 2000, 2100, 2150 and 2200 (or years 0, 100, 150, and 200 respectively) with scenario S4.3.2. The age structure and patch size distributions of existing forests are already in the desired states and are maintained for the entire planning horizon.

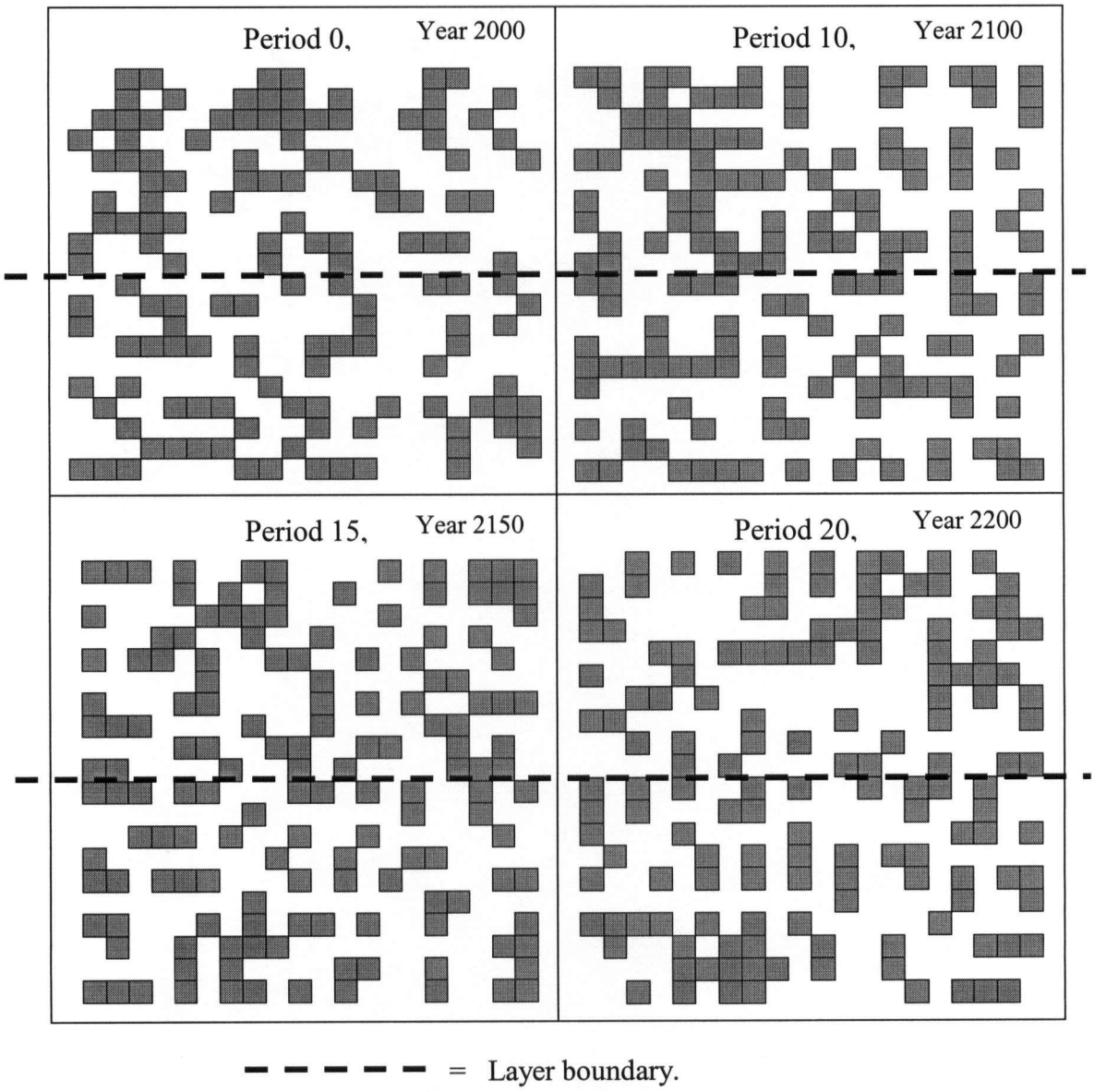


Figure 4.20 - Four snapshots of old (>100 years) stands for scenario S4.3.2 (Polygons are randomly 0-160 years at the start).

Results of Scenario S4.3.3

(All polygons are 50 years old in the initial forest)

Figure 4.21 and 4.22 illustrate the temporal changes of old stands (>100 years) and patches in layer 1. Because the initial inventory is young (50 years), it requires 60 years to reach the old (>100 years) stand and patch targets. After 60 years, the desired states are maintained for the remainder of planning horizon within a 10% tolerance. By period 5, all stands in layer 1 reach 100 years old, and about 30% of the layer is harvested in periods 5 and 6. All old stands become one large patch that is gradually divided into small patches, however, the desired patch target is maintained for the remainder of the planning horizon.

Figure 4.23 and 4.24 depict the temporal changes of old stands (>100 years) and patches in layer 2. Similar to layer 1, it takes 60 years to reach the old stand and patch targets, and the desired states are maintained for the rest of planning horizon. At period 6, all stands in layer 2 have reached 100 years, and about 40% of the layer has been harvested at periods 5 and 6. About 90% of the old stands are in sizes equal or greater than 40 hectares. The amount of old large patches is gradually reduced to 70% and maintained for the rest of the planning horizon. In comparing Figure 4.22 and 4.24, the patch targets for both layer 1 and layer 2 are achieved even though these two layers have very different patch targets.

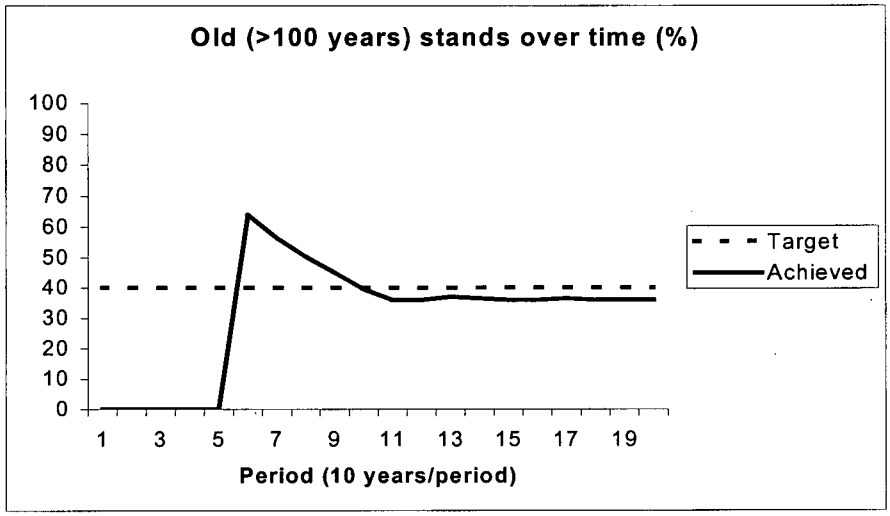


Figure 4.21 - Old (>100 years) stands in layer 1 for scenario S4.3.3 (All polygons are 50 years old at the start).

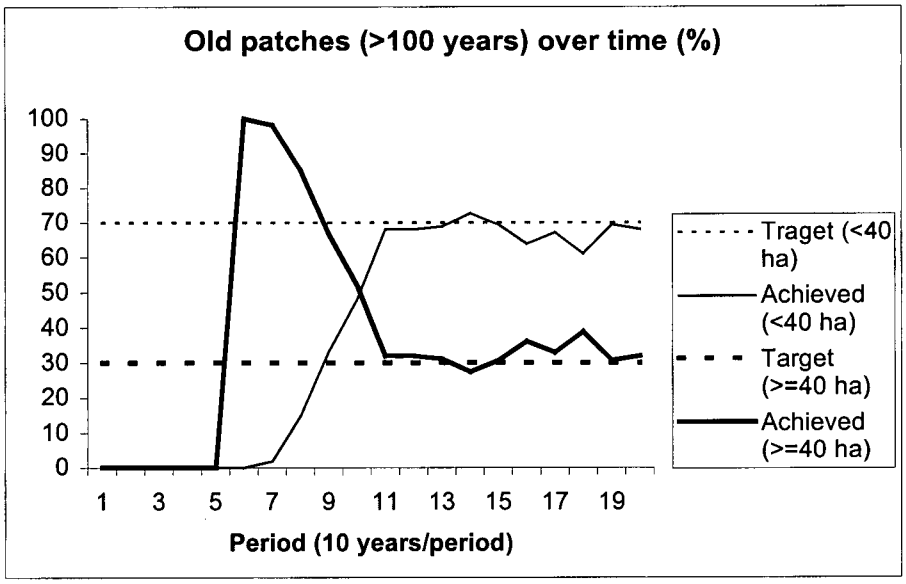


Figure 4.22 - Old (>100 years) patches in layer 1 for scenario S4.3.3 (All polygons are 50 years old at the start).

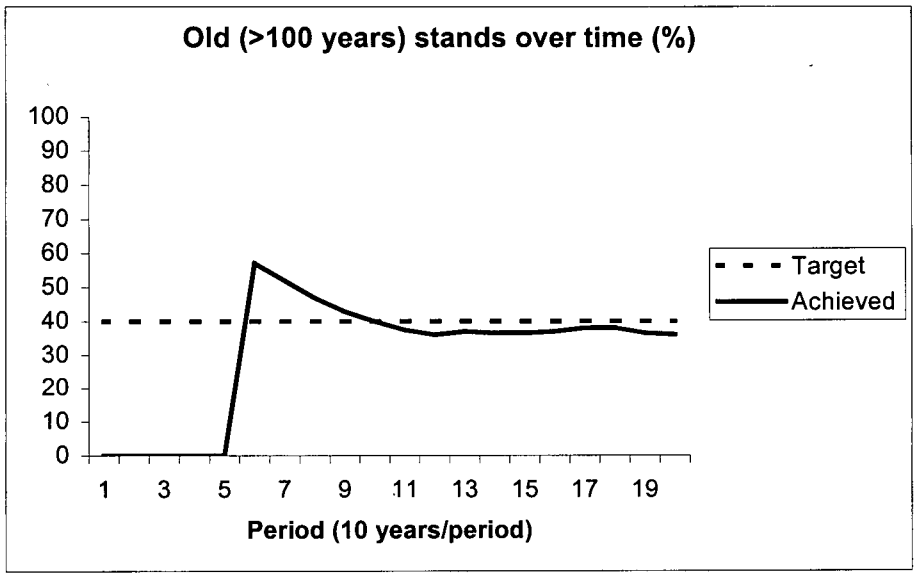


Figure 4.23 - Old (>100 years) stands in layer 2 for scenario S4.3.3
(All polygons are 50 years old at the start).

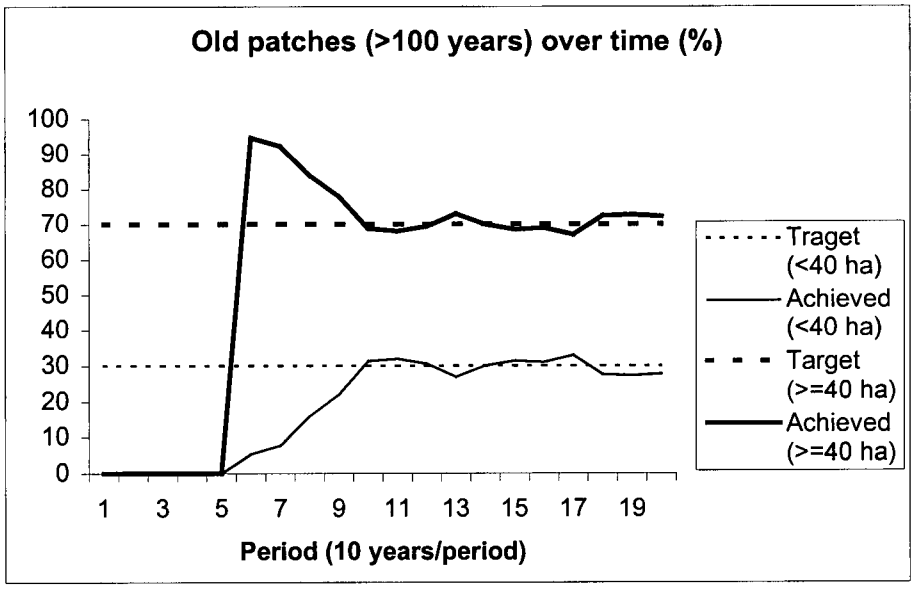


Figure 4.24 - Old (>100 years) patches in layer 2 for scenario S4.3.3
(All polygons are 50 years old at the start).

Figure 4.25 shows four snapshots of the old (>100 years) patches at years 2000, 2100, 2150 and 2200 (or years 0, 100, 150 and 200, respectively). The current forest does not have any old stands or patches. The desired states are met in period 7 and maintained for the rest of planning horizon.

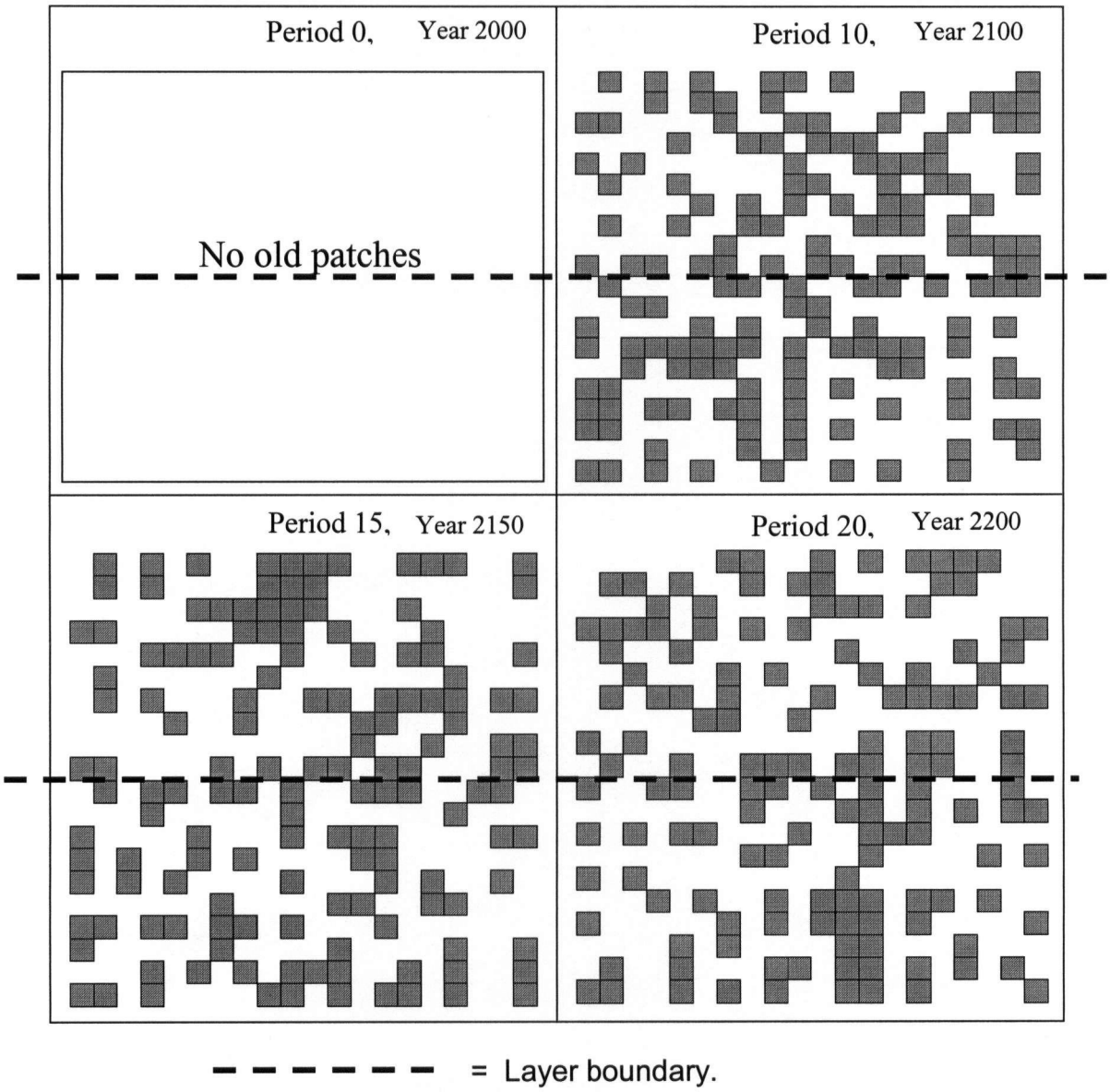


Figure 4.25 - Four snapshots of old (>100 years) stands for scenario S4.3.3 (All polygons are 50 years old at the start).

Results of Scenario S4.3.4

(Polygon ages are randomly 0-50 years in the initial forest)

Figure 4.26 and 4.27 illustrate the temporal changes of old stands (>100 years) and patches in layer 1. Since the initial inventory ages are random between 0 and 50, it takes 95 years to reach the old stand target. After 95 years, the desired states are maintained for the rest of planning horizon (10% tolerance). At period 7, there are only 210 hectares (about 10% of the layer) in old stands and 100% of them are in small patch sizes (<40 hectares).

Figure 4.28 and 4.29 show the temporal changes of old stands (>100 years) and patches in layer 2. Similar to layer 1, it takes 95 years to reach the old stand target. The old patch targets are met by period 7, at which point the desired states are maintained for the remainder of the planning horizon (within a 10% tolerance).

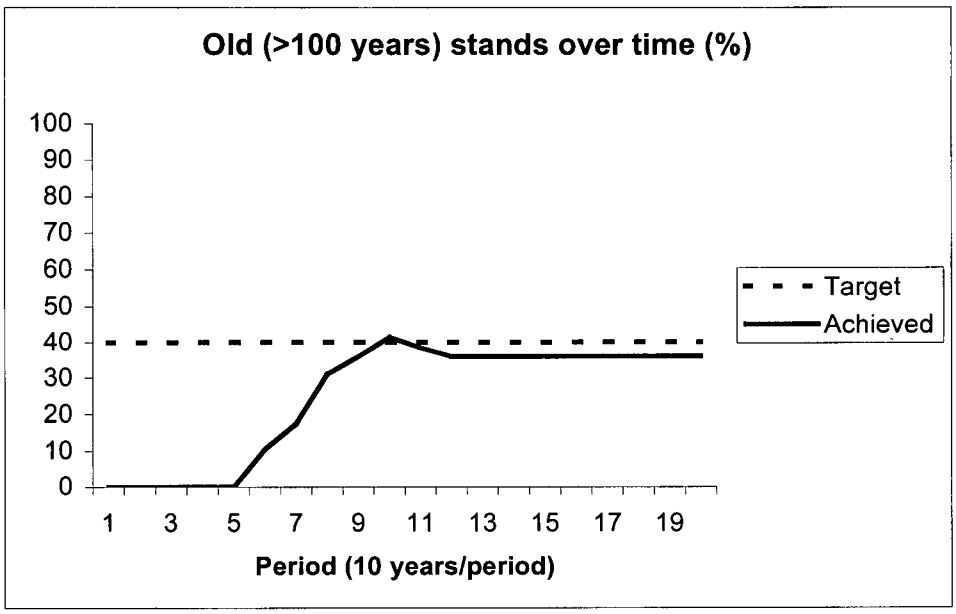


Figure 4.26 - Old (>100 years) stands in layer 1 for scenario S4.3.4 (Polygon ages are randomly 0-50 years at the start).

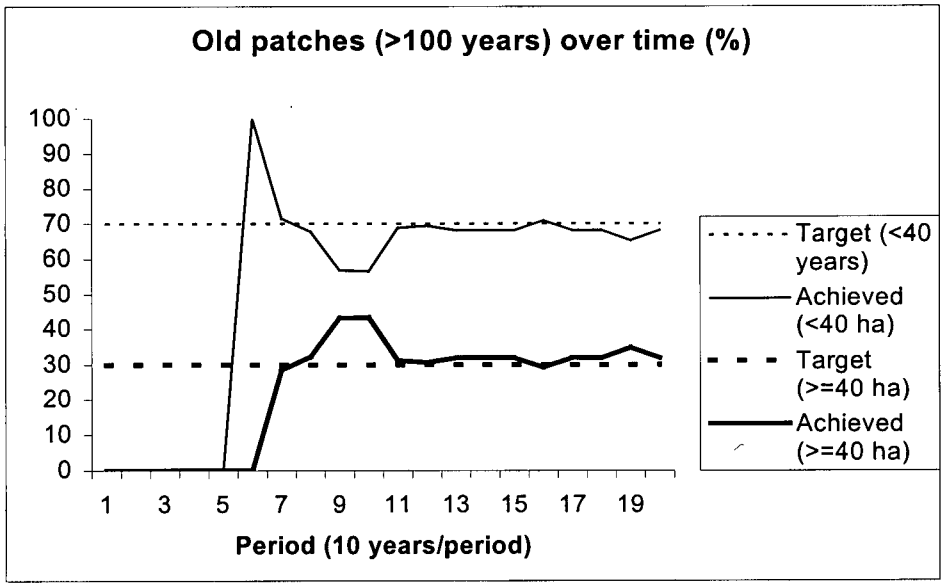


Figure 4.27 - Old (>100 years) patches in layer 1 for scenario S4.3.4 (Polygon ages are randomly 0-50 years at the start).

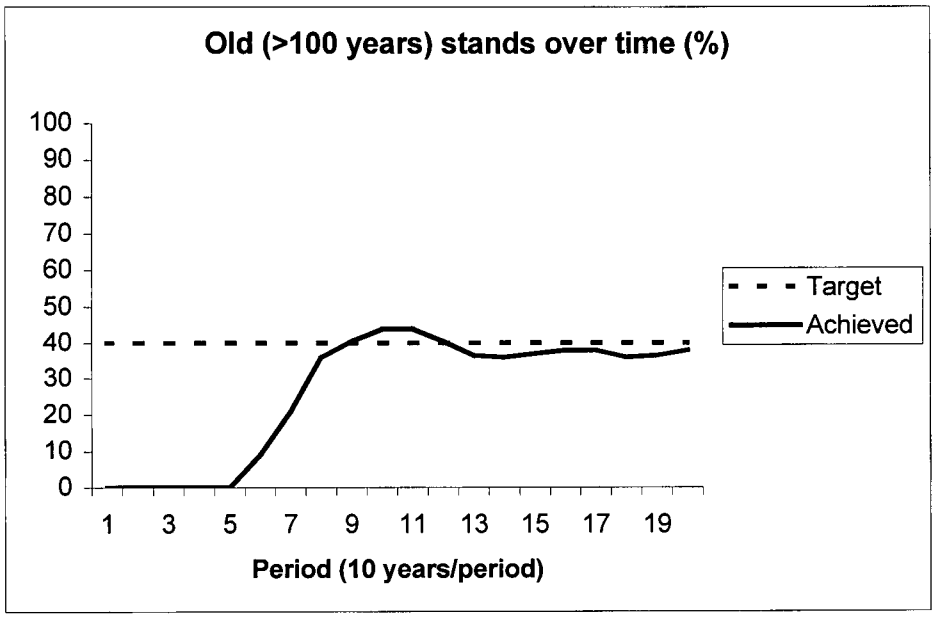


Figure 4.28 - Old (>100 years) stands in layer 2 for scenario S4.3.4 (Polygon ages are randomly 0-50 years at the start).

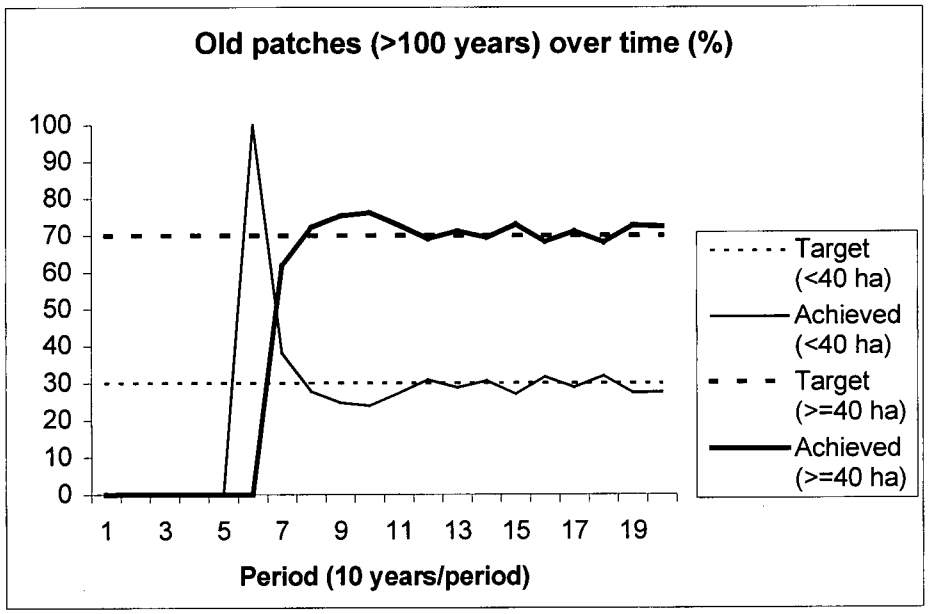


Figure 4.29 - Old (>100 years) patches in layer 2 for scenario S4.3.4 (Polygon ages are randomly 0-50 years at the start).

Figure 4.30 shows the four snapshots of the old (>100 years) patches at years 2000, 2100, 2150 and 2200 (or years 0, 100, 150, and 200, respectively). The current forest does not have any old (>100 years) stands or patches. The desired states are met in year 2100 and maintained for the remainder of planning horizon.

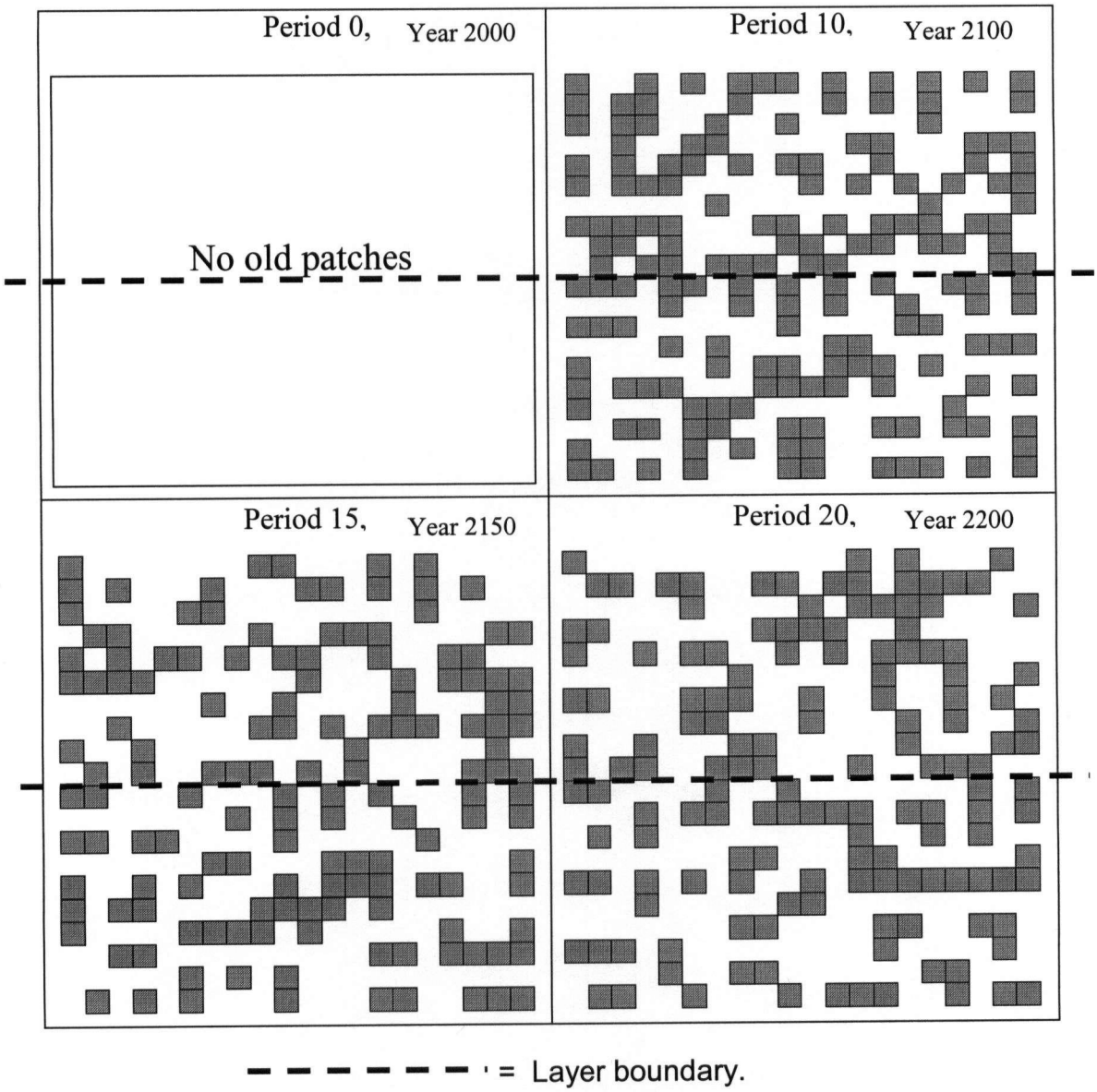


Figure 4.30 - Four snapshots of old (>100 years) stands for scenario S4.3.4 (Polygon ages are randomly 0-50 years at the start).

From these four scenarios, I conclude that FSOS can achieve the desired forest states from different initial inventories, and that the time to achieve the desired state increases the further the target is from the initial inventory.

4.4 Sensitivity of Timber Flows and Old Patches to Natural Disturbances

To analyze the sensitivity of timber flows to natural disturbance rates and test whether the model can build desired age and patch size distributions with different natural disturbance rates, three scenarios (Table 4.9, Figures 4.35 and 4.36) are developed. To create a complex forest transformation problem, the following assumptions are made: 1) the existing forest is created by following 10-year adjacency constraints for 30 years, 2) 25% of the area is recently regenerated; 3) 25% of the area is 10-year old forest; 25% of the area is 20-year old forest; and 4) 25% of the area is 175-year old forest.

The following age structure targets (in % of area) are applied. 1) Maximum target for young stands (<=20 years) is 25%, and minimum target for old stands (>=100 years) is 20%. The old (>=100 years) patch targets (in % of old stand area) are: 1) maximum target for small size patches (<=10 hectares) is 33%, 2) maximum target for medium size patches (<10 and <40 hectares) is 33%, and 3) minimum target for larger size patches (>=40 hectares) is 34%. Natural disturbances are randomly generated before each run.

Table 4.9 – Timber flows with different natural disturbance scenarios.

Scenario	S4.4.1	S4.4.2	S4.4.3
Natural disturbance rate	**0%/year**	**0.125%/year**	**0.25%/year**
Average timber flows (% reduced)	22,680(0%)	16,958(25.2%)	12,201 (46.2%)

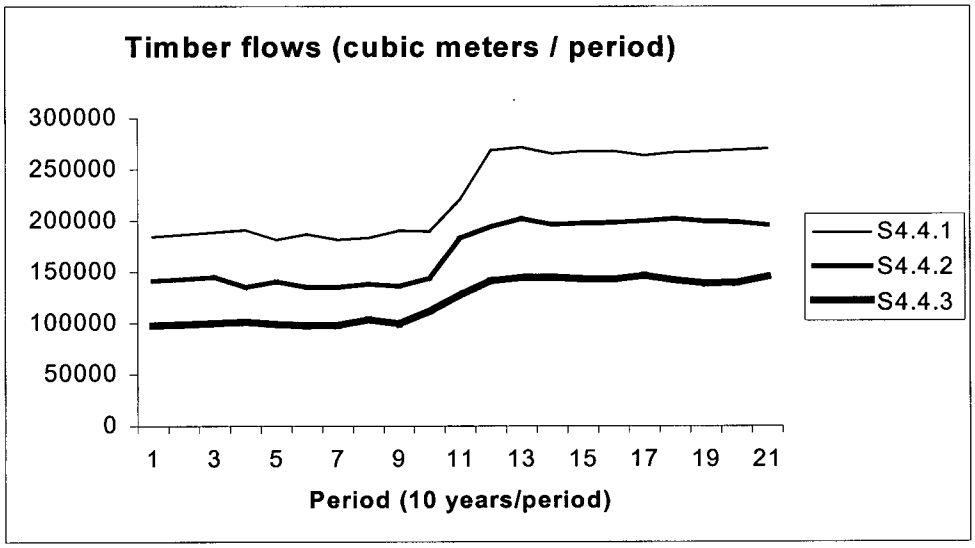


Figure 4.31 - Timber flows with different natural disturbance rates for scenarios S4.4.1, S4.4.2, and S4.4.3.

On average, timber flows are reduced 25.2% with a 0.125%/year natural disturbance rate and reduced 46.2% with a 0.25%/year natural disturbance rate (Table 4.9 and Figure 4.31). Timber flows are low from period 1 to 10 because there are excessive young stands at periods 1 and 2 (Figure 4.32) and there not enough old stands from period 2 to 10 (Figure 4.33). Patch targets can not be achieved until period 10 (Figure 4.34). The age class and patch targets greatly affect timber flows.

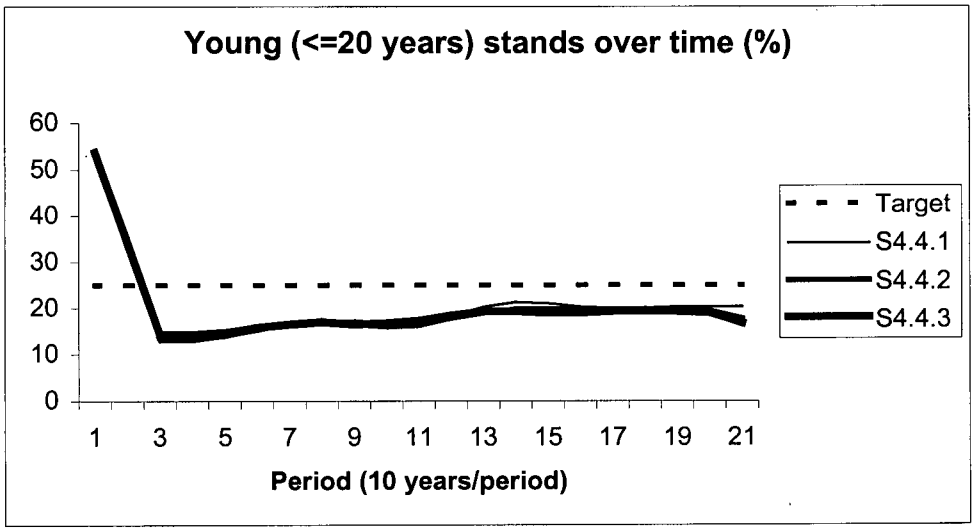


Figure 4.32 - Young stands (<=20 years) with different natural disturbance rates for scenarios S4.4.1, S4.4.2, and S4.4.3.

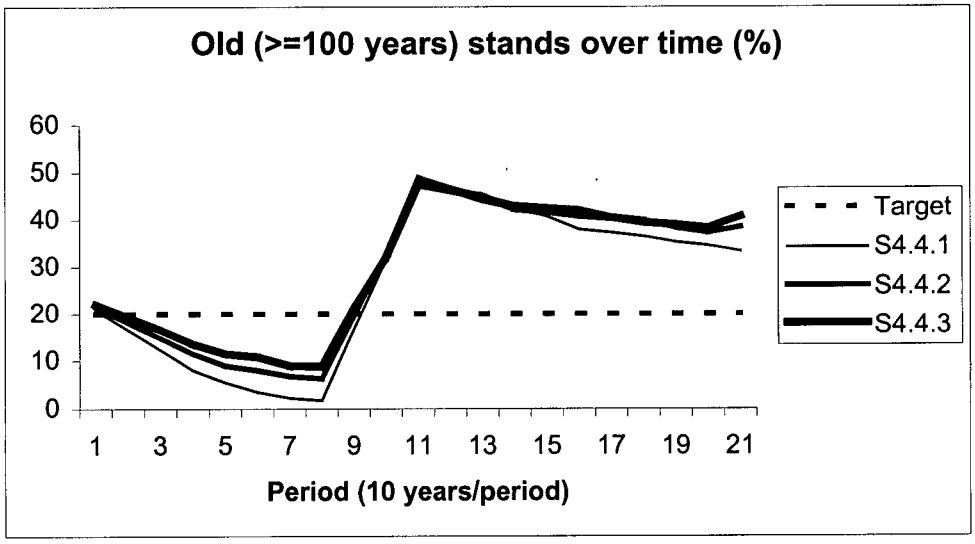
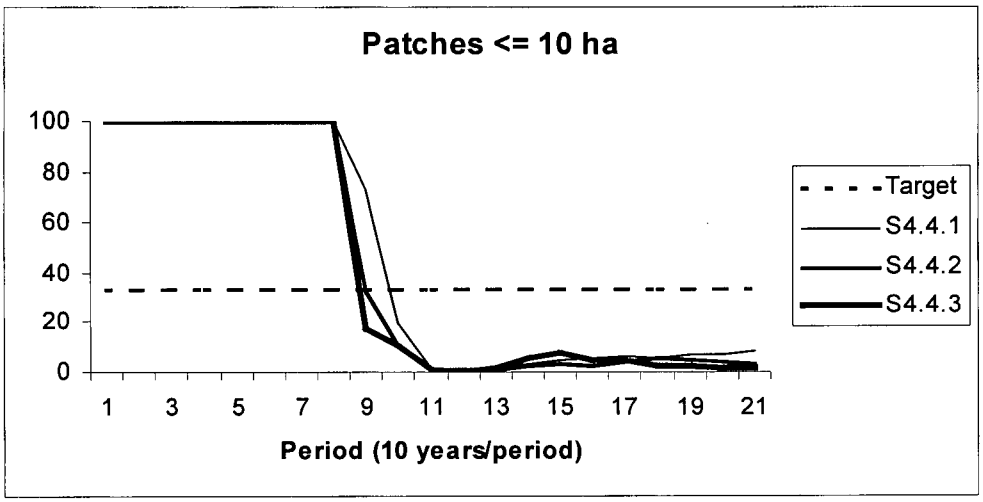
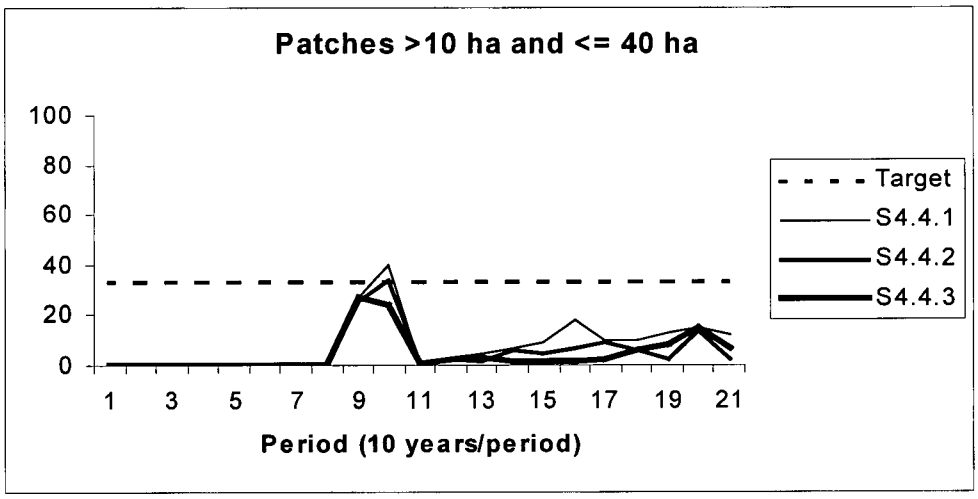


Figure 4.33 - Old stands (>=100 years) with different natural disturbance rates for scenarios S4.4.1, S4.4.2, and S4.4.3.





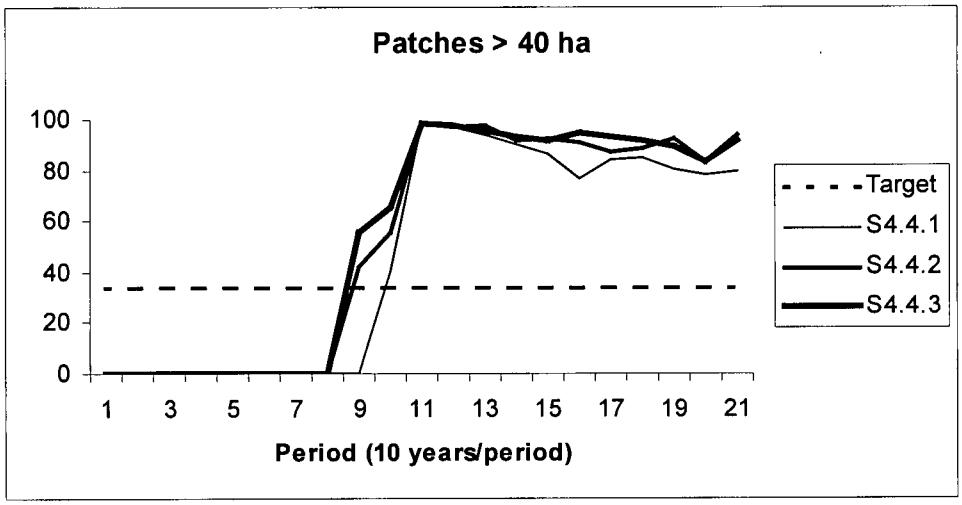


Figure 4.34 - Old (>=100 years) patches with natural disturbance for scenarios S4.4.1, S4.4.2, and S4.4.3.

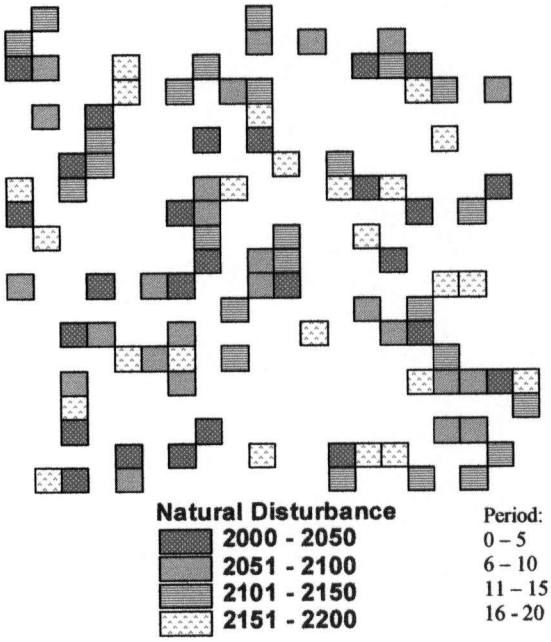


Figure 4.35 – The natural disturbance pattern for scenario S4.4.2 (0.125% / year random).

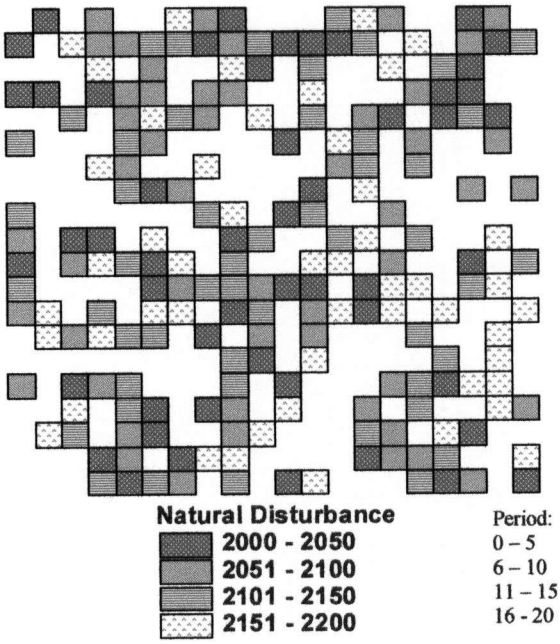


Figure 4.36 – The natural disturbance pattern for scenario S4.4.3 (0.25%/year random).

Figures 4.37, 4.38 and 4.39 show that the natural disturbance rates slightly affect old stands and large old patch achievements. However, the natural disturbances greatly impact the timber flows (Figure 4.31). With the three natural disturbance rates, the same old stand and large old patch targets can be achieved. Therefore, I conclude that the model is working as designed, and that it is able to find harvest strategies that meet the targets (Figures 4.37, 4.38 and 4.39). This is an advantage of target-oriented forest planning.

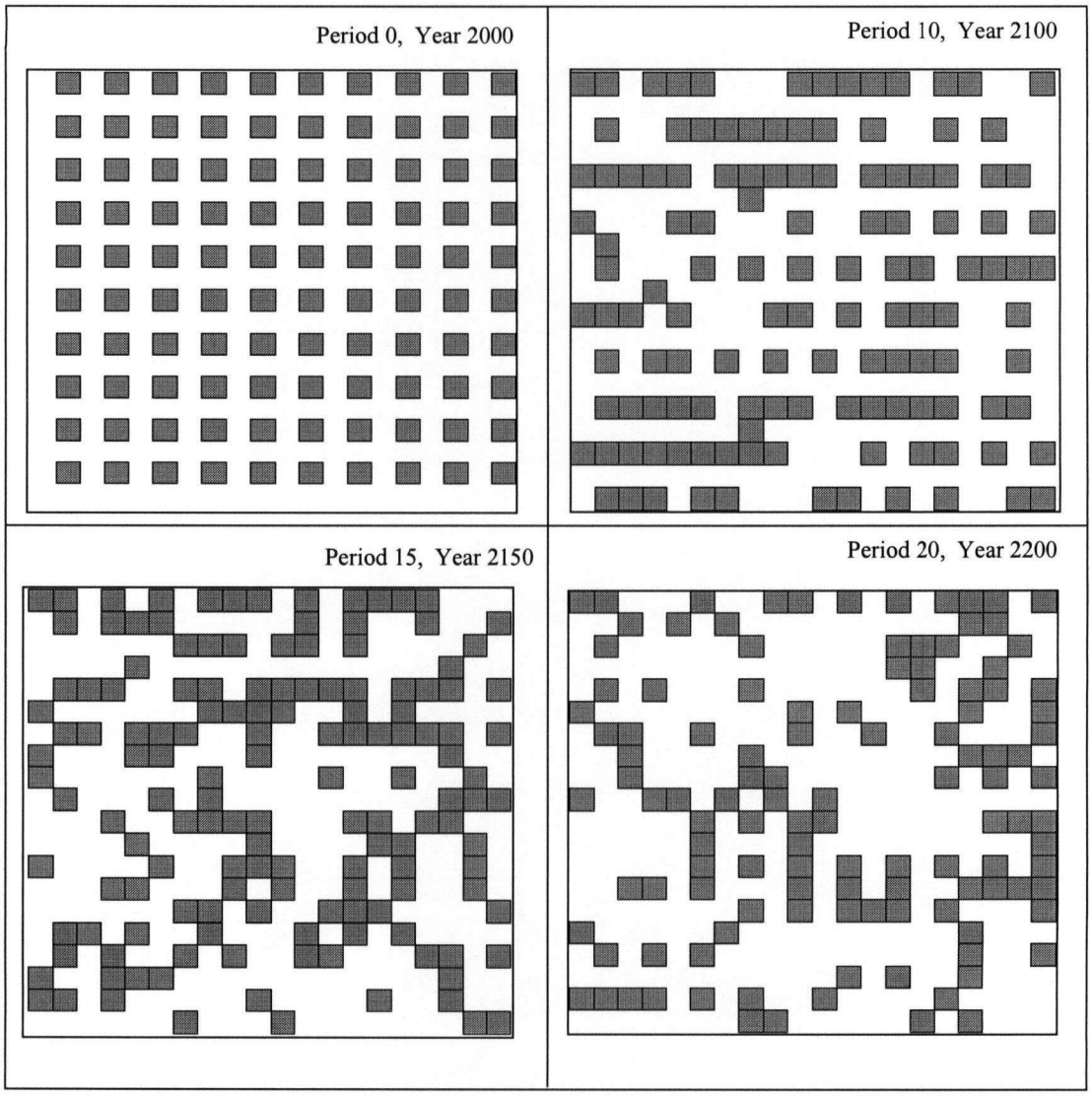


Figure 4.37 - Snapshots of old patches without natural disturbance (Scenario S4.4.1).

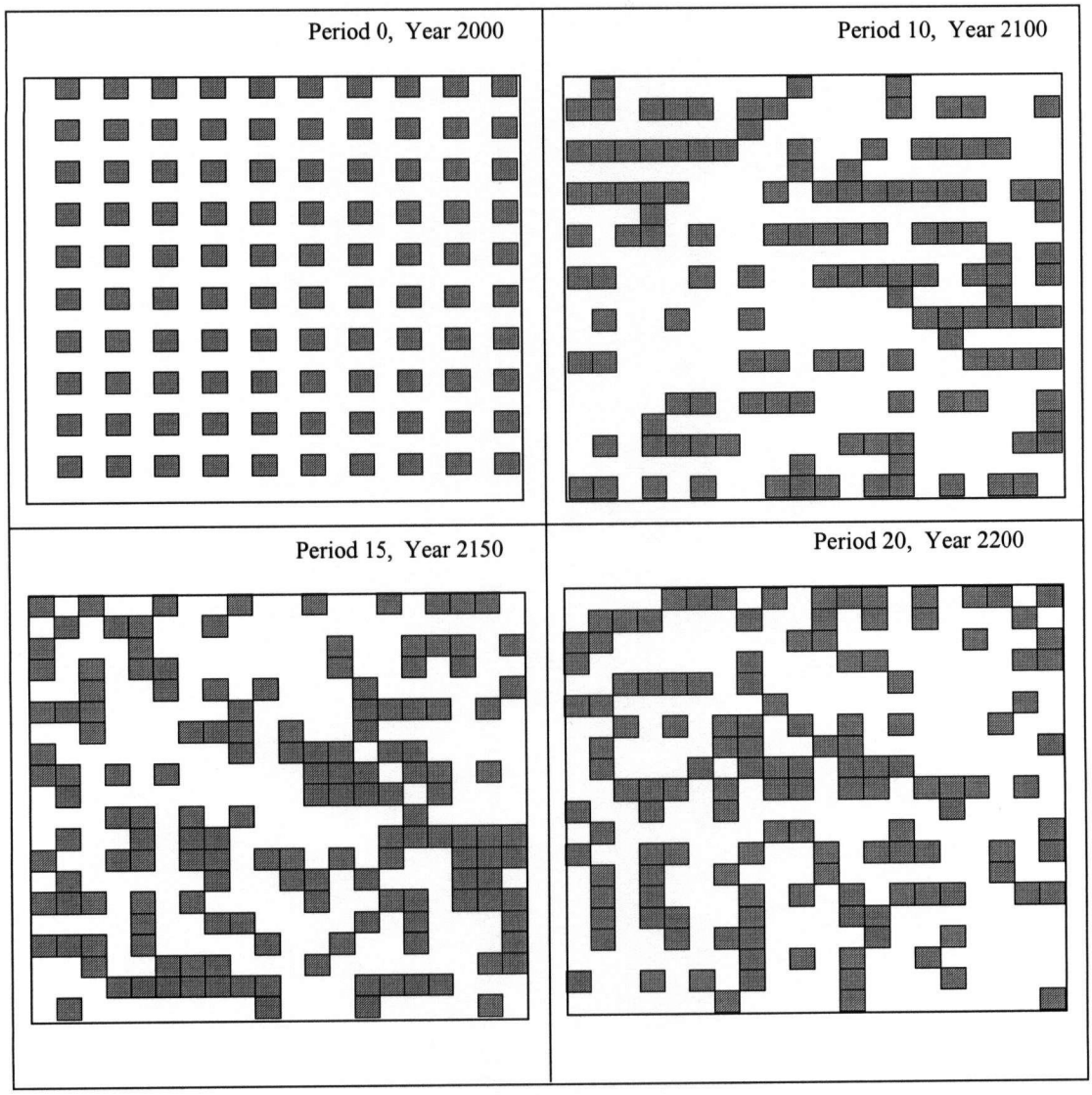


Figure 4.38 - Snapshots of old patches with 0.125%/year natural disturbance rate (Scenario S4.4.2).

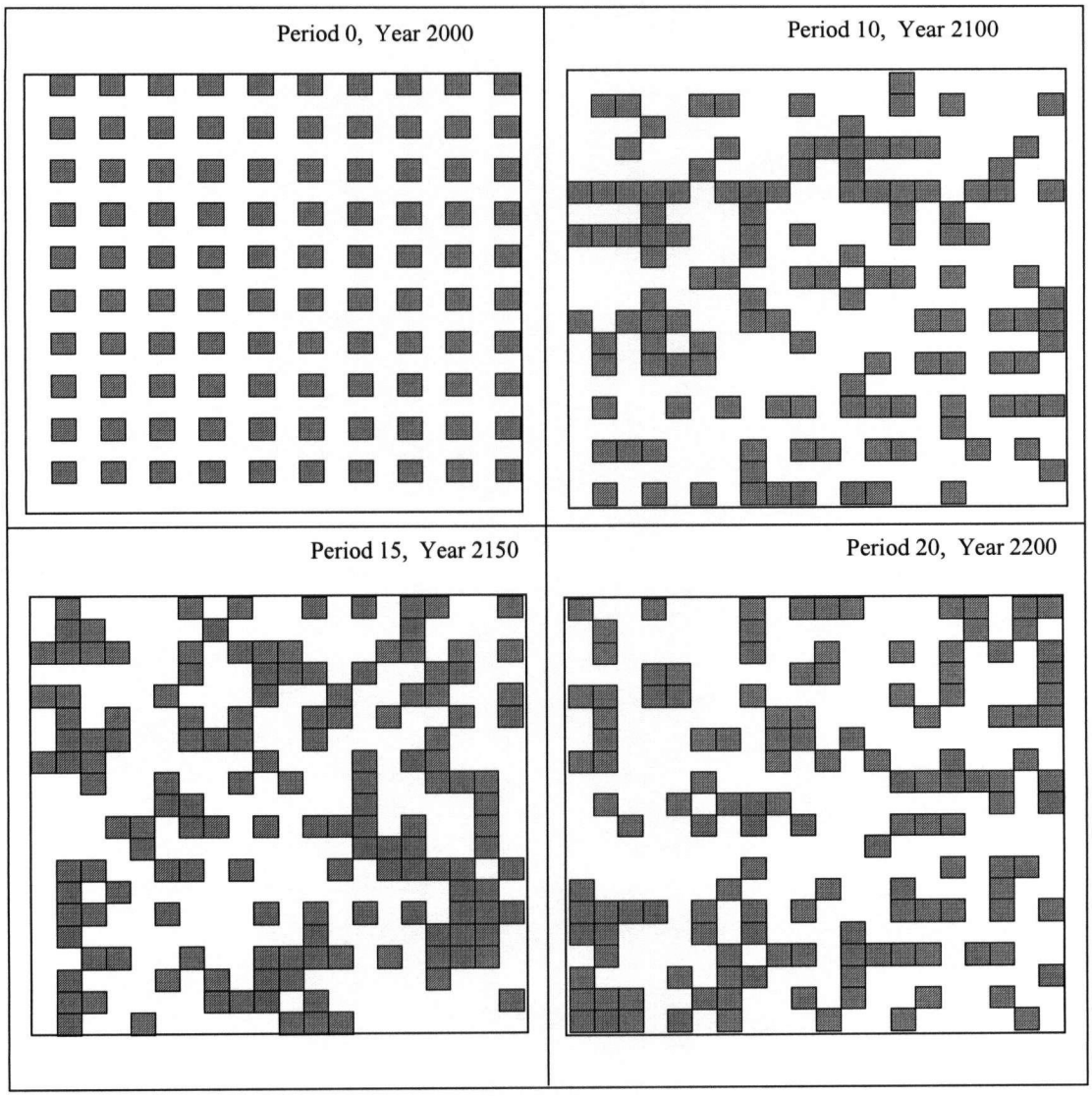


Figure 4.39 - Snapshots of old patches with 0.25%/year natural disturbance rate (scenario S4.4.3).

4.5 Comparison with ATLAS

The objective of comparing FSOS and ATLAS is to demonstrate differences between a rule-based, simulation model and a target-oriented model.

ATLAS (A Tactical Landscape Analysis System, Nelson 1995) is a typical time-step rule-based simulation model developed at the University of British Columbia and has been used for about a decade.

A 400-grid data set is used for all FSOS and ATLAS runs in this section. To make the forest transformation more difficult, the 400-grid polygons are sorted into 4 non-adjacent groups and are assigned ages 0, 10, 20, and 175 years, respectively. All stands use the same yield curves. The minimum harvest age is 80 years and all polygons are 10 hectares.

Three ATLAS runs with different harvest rules and three FSOS runs with different weighting scenarios are made. The targets for FSOS runs are used as constraints for ATLAS runs.

4.5.1 ATLAS Runs

The harvest-scheduling rules are identified first.

The age structure constraints for the entire area are:

1) maximum 25% of area less than or equal to 20 years old, and
2) minimum 20% of area greater than or equal to 100 years.

Instead of specifying a patch size distribution, ATLAS created a block size distribution by aggregating polygons before the runs. The distribution is:

1) 33% of area in 10 ha blocks,

2) 33% of area in 40 ha blocks, and

3) 34% of area in 120 ha blocks.

A 20-year adjacency green-up constraint is applied to all three scenarios. The differences in the three scenarios are described in Table 4.10. A harvest priority list of potential cutblocks is established based on the stand ages. The harvest-rule is "oldest first", subject to all constraints. In scenario S4.5.1.3, blocks are sorted into four non-adjacent groups. Each group is assigned a harvest priority and the "oldest first" rule is applied within the group.

Table 4.10 - Descriptions of ATLAS scenarios S4.5.1.1, S4.5.1.2, and S4.5.1.3.

Scenario	S4.5.1.1	S4.5.1.2	S4.5.1.3
Description	Whole block can not be harvested if one or more polygons are under the minimum harvest age.	Polygons that are at least as old as the minimum harvest age can be cut within a block.	Blocks are sorted into 4, non-adjacent groups. These groups are used as harvest priorities. The result is a non-adjacency cutting pattern.

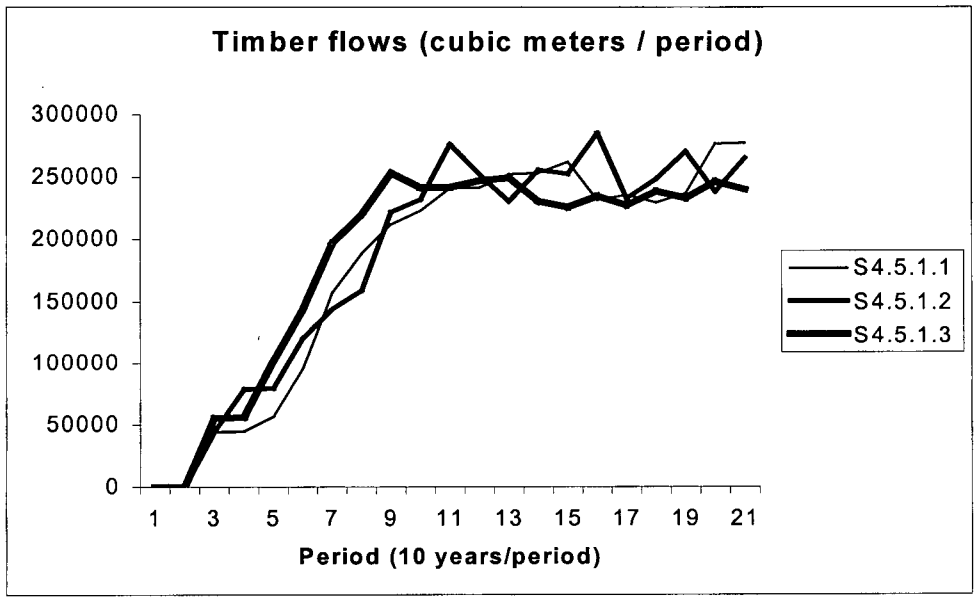


Figure 4.40 - Timber flow for ATLAS scenarios S4.5.1.1, S4.5.1.2, and S4.5.1. 3.

Figure 4.40 shows the timber flows from the three ATLAS runs. The timber flow during first two decades is zero because the young stand requirement is binding (Figure 4.41). During periods 4-8, the old stand requirement is binding (Figure 4.42). The timber flows are similar for the three scenarios when the forest reaches a stable state after period 9. The timber flow for Scenario S4.5.1.1 is lower than Scenario S.4.5.1.2 between period 4 and 9 (Figure 4.40) because a less flexible minimum harvest age within cut blocks is applied for Scenario S4.5.1.1.

The three scenarios have similar results in terms of timber flows, forest age structures and old patch patterns (Figures 4.43, 5.44, 5.45, and 5.46). FSOS was used to calculate age structures and patches from the ATLAS simulations. Figure 4.41 shows the temporal changes of young stands (<=20 years) for the ATLAS runs. The percentage of young stands in the existing forest exceeds the

constraint, and this prevents timber harvests for more than 2 periods. Figure 4.42 shows that the percentage of old stands (>=100 years) is limiting timber production from periods 4 to 8. Figure 4.43 illustrates that the patch targets cannot be reached until period 8 because of the existing forest patterns (Figure 4.44, 4.45 and 4.46). After period 8, most of the old stands are in patches greater than 40 hectares.

The results show that block size distributions can not guarantee the patch size distributions. In this example, very few small old patches are created even when 33% of the blocks are 10 hectares and 33% are 40 hectares. The small blocks (<=40 ha) are aggregated to large patches (Figures 5.44, 5.45, and 5.46) over time. Scenarios S4.5.1.1 and S4.5.1.2 created similar patch patterns (Figure 5.44 and 5.45) because the harvest rules are quiet similar, especially over the long-term. Scenario 4.5.1.3 generated a very different patch pattern from other scenarios because of the "non-adjacency grouping" harvest rule.

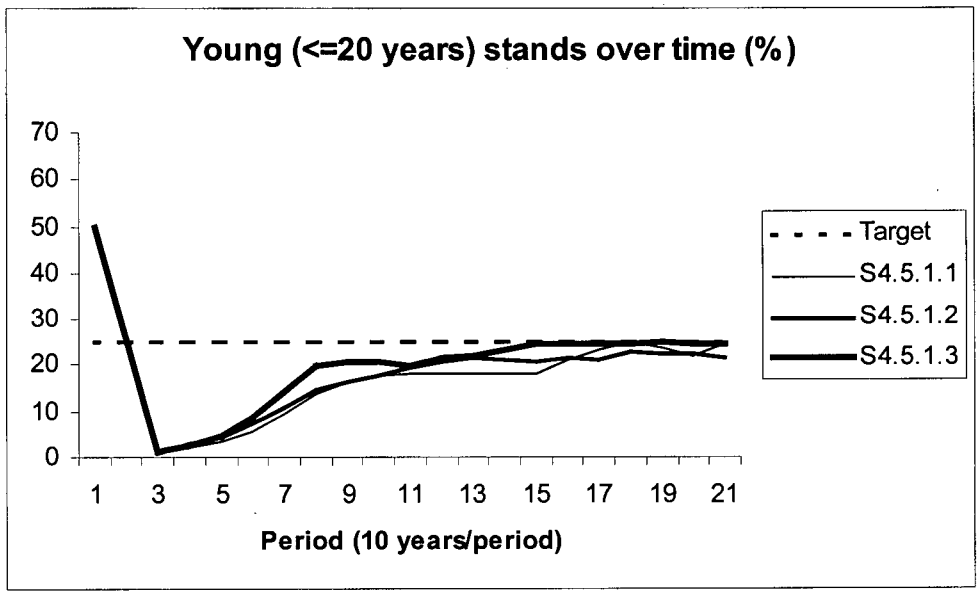


Figure 4.41 – Young (<=20 years) stands for ATLAS scenarios S4.5.1.1, S4.5.1.2, and S4.5.1.3.

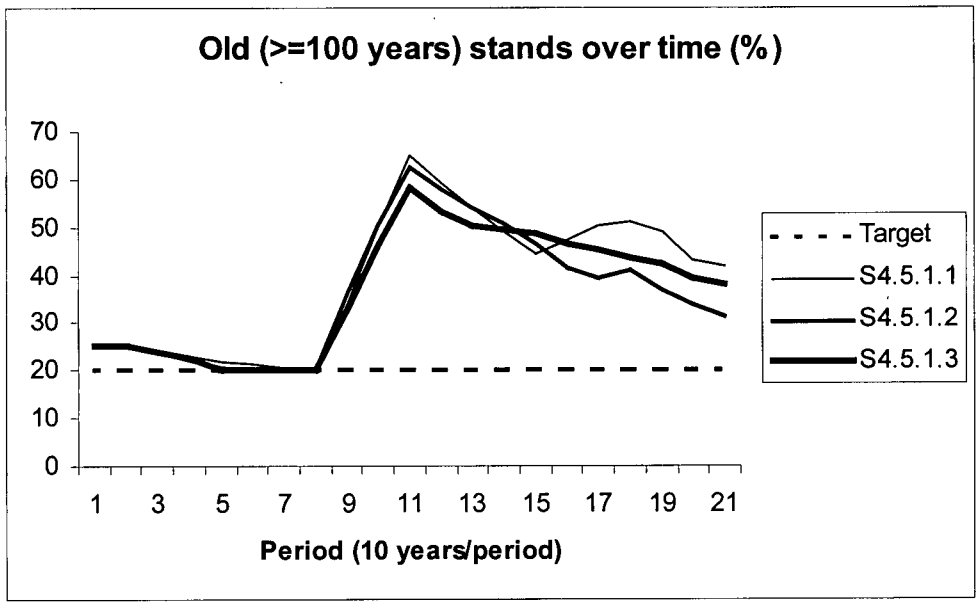


Figure 4.42 - Old (>=100 years) stands for ATLAS scenarios S4.5.1.1, S4.5.1.2, and S4.5.1.3.

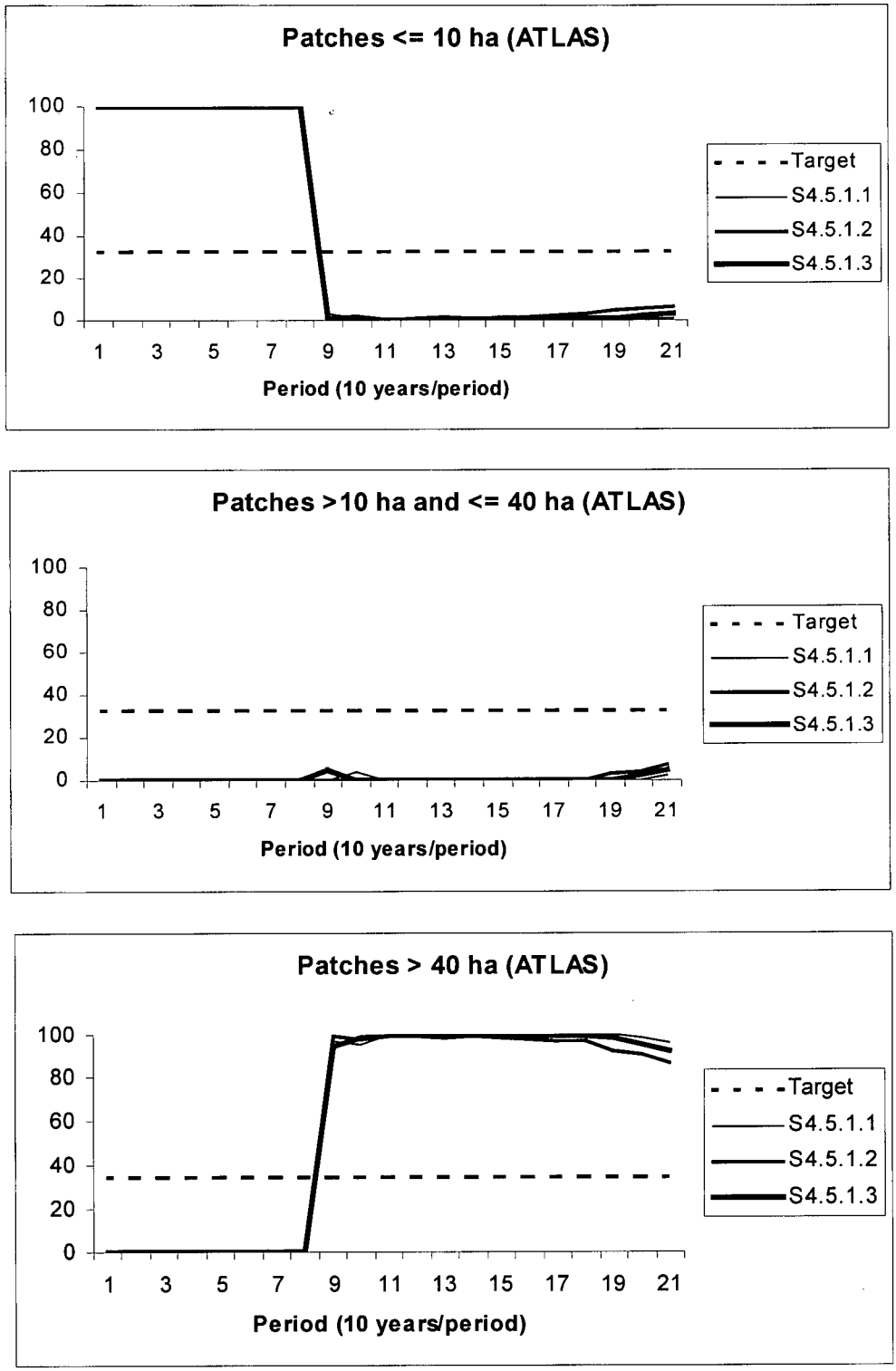


Figure 4.43 - Old (>=100 years) patches for ATLAS scenarios S4.5.1.1, S4.5.1.2, and S4.5.1.3.

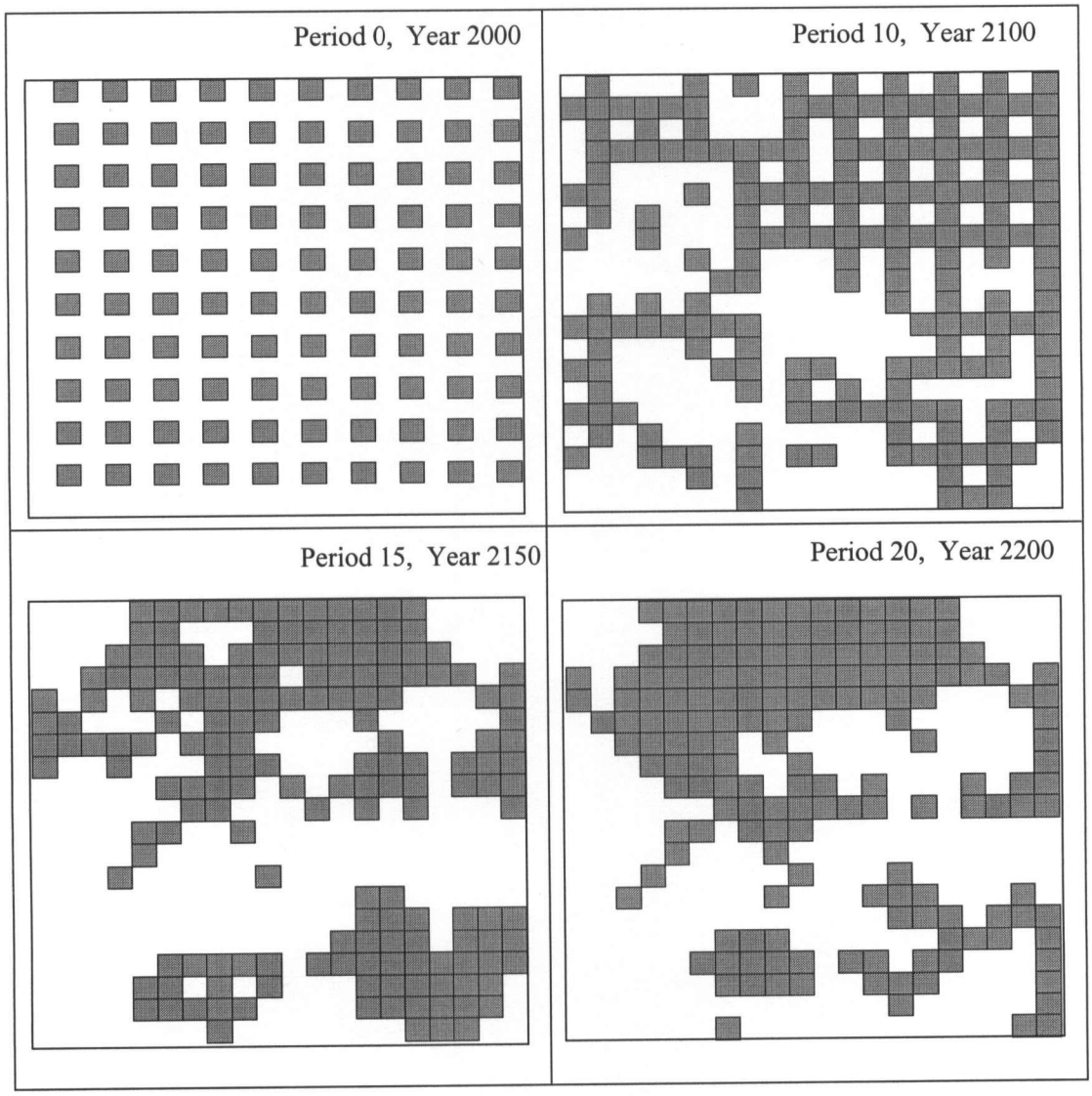


Figure 4.44 - Four snapshots of old patches for the ATLAS scenario S4.5.1.1.

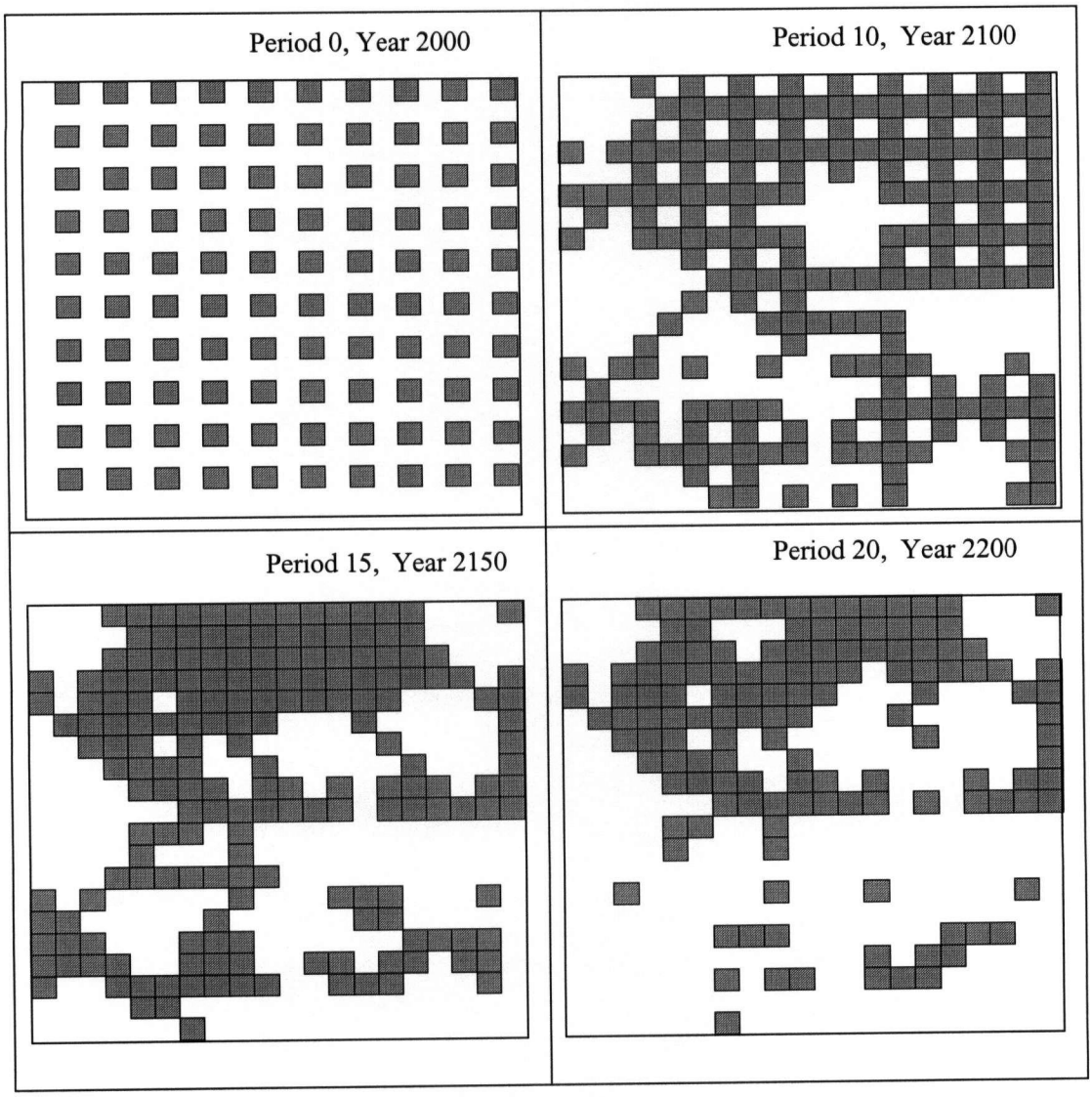


Figure 4.45 - Four snapshots of old patches for the ATLAS scenario S4.5.1.2.

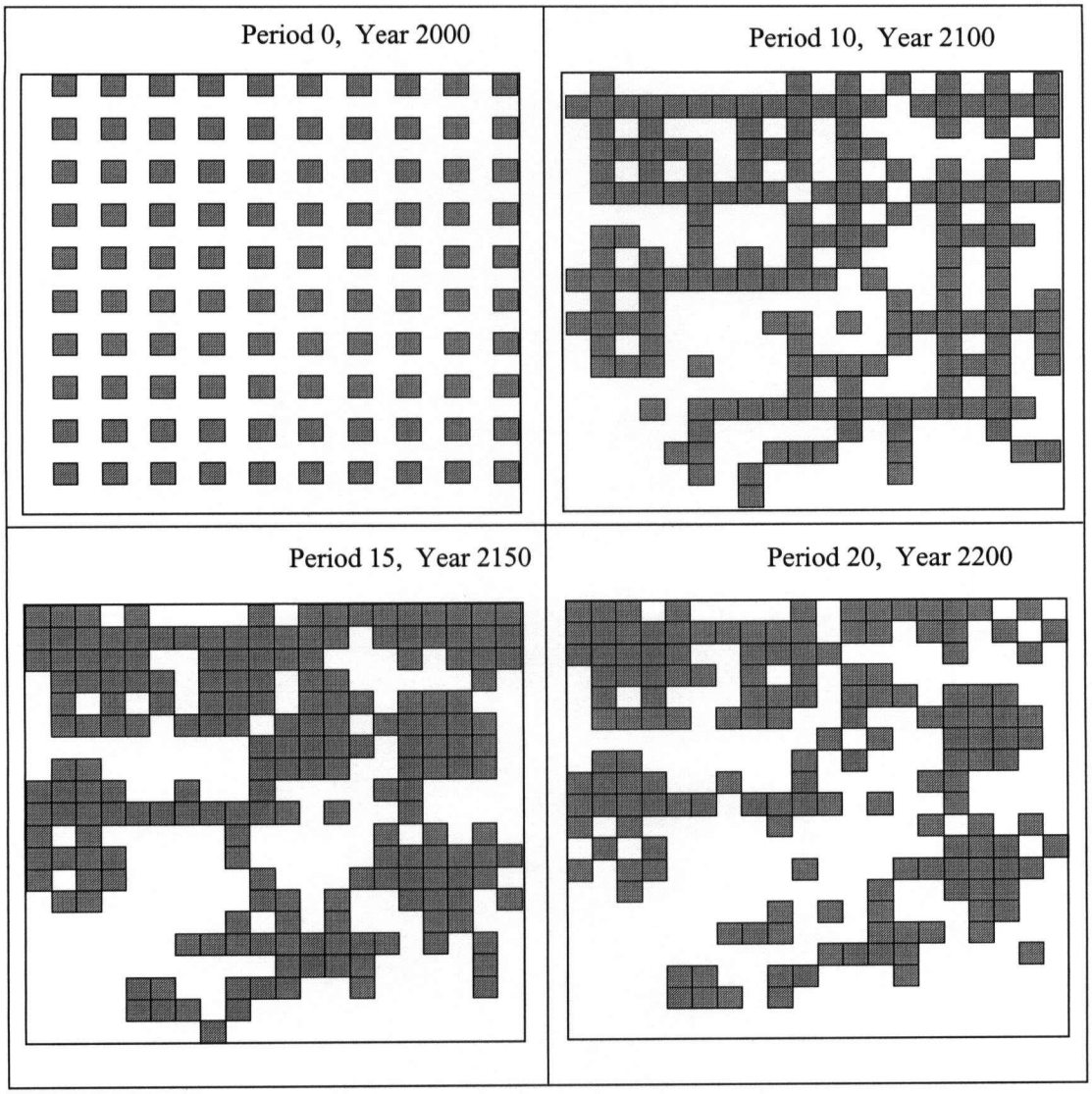


Figure 4.46 - Four snapshots of old patches for the ATLAS scenario S4.5.1.3.

After finding that young and old stand requirements are binding, the analysts can relax the constraints for the binding periods and re-run the simulations. This is repeated until an acceptable solution, in terms of forest structure and timber supply, is found.

4.5.2 FSOS Runs

Because the two models are so different, it is difficult to compare FSOS and ATLAS directly. The parameters for the FSOS runs were set as close as possible to the constraints of the ATLAS runs. The age structure targets (in % of the area) are: 1) maximum target for young stands (<=20 years) is 25%, and minimum target for old stands (>=100 years) is 20%. The old (>=100 years) patch targets (expressed in % of the old stand area) are: 1) maximum target for the small size patches (<=10 hectares) is 33%, 2) maximum target for the medium size patches (<10 and <40 hectares) is 33%, and 3) minimum target for the larger size patches (>=40 hectares) is 34%. An important difference between ATLAS and FSOS is in this larger patch size. ATLAS uses pre-blocked 120 ha blocks while FSOS tries to build blocks >= 40 ha (not 120 ha).

Because the age structure is the major factor that impacts timber flows for ATLAS simulation runs, three scenarios (Table 4.11) with different weightings of age structures are tested. These three scenarios differ only in the age structure weightings.

Table 4.11 -Age structure weights for scenarios S4.5.2.1, S4.5.2.2, and S4.5.2.3.

Scenario	S4.5.2.1	S4.5.2.2	S4.5.2.3
Weight for age structure	0.0001	0.01	1

Figure 4.47 illustrates the timber flows of the three FSOS runs. In scenario S4.5.2.1 and S4.5.2.2, even timber flows within a 10% tolerance can be

achieved and maintained over the entire planning horizon. It requires a few decades to achieve the age structure (Figures 4.48 and 4.49). In scenario S4.5.2.3, the age structure can be achieved earlier if the weight of the age structure is increased (Figures 4.48 and 49). However, the timber flows must be reduced during first few decades similar to the ATLAS runs (Figure 4.47). Figures 4.50 shows that the patch targets cannot be reached until period 9 (90 years later). The old (>=100 years) large patches (>40 ha) targets are achieved one period earlier in scenario S4.5.2.3 than scenario S4.5.2.1 because higher age structure weights are used in the patch penalty function. Note that the young stand requirement is not met in periods 1-2 and the old stand requirement is not met in periods 1–9 (Figure 4.49). Where old stands are already scarce, harvesting as in Scenarios S4.5.2.1 and S4.5.2.2 is probably unacceptable.

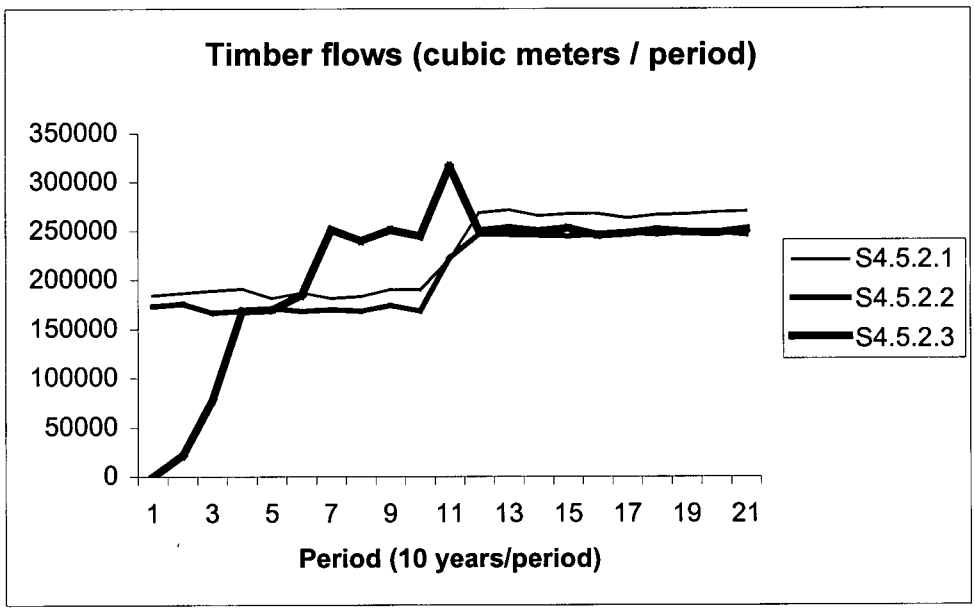


Figure 4.47 - Timber flows for FSOS scenarios S4.5.2.1, S4.5.2.2, and S4.5.2.3.

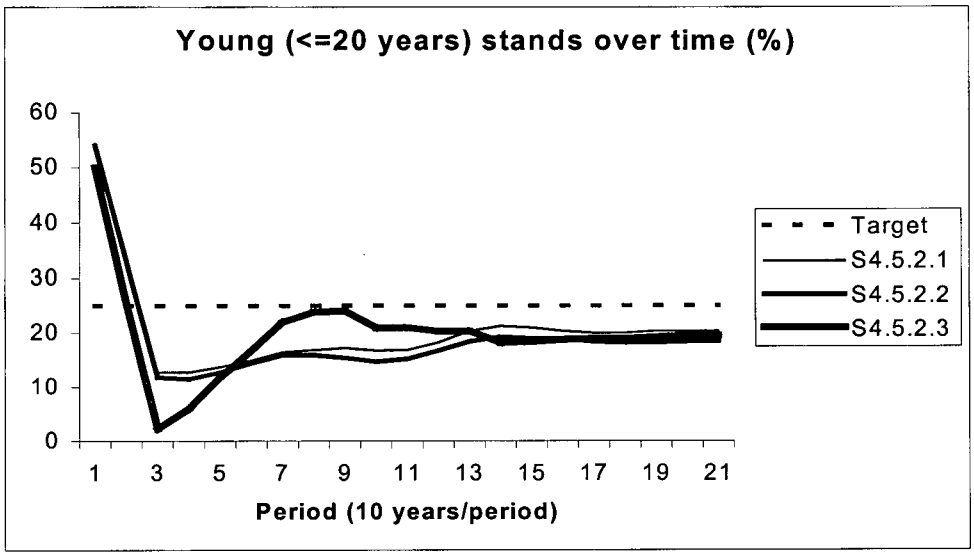


Figure 4.48 - Young (<=20 years) stands for FSOS scenarios S4.5.2.1, S4.5.2.2, and S4.5.2.3.

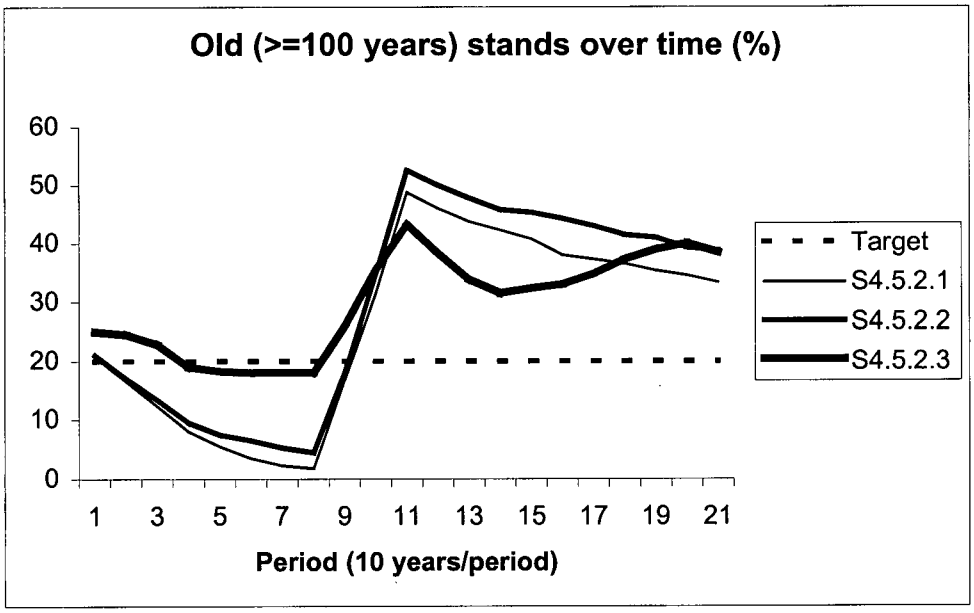
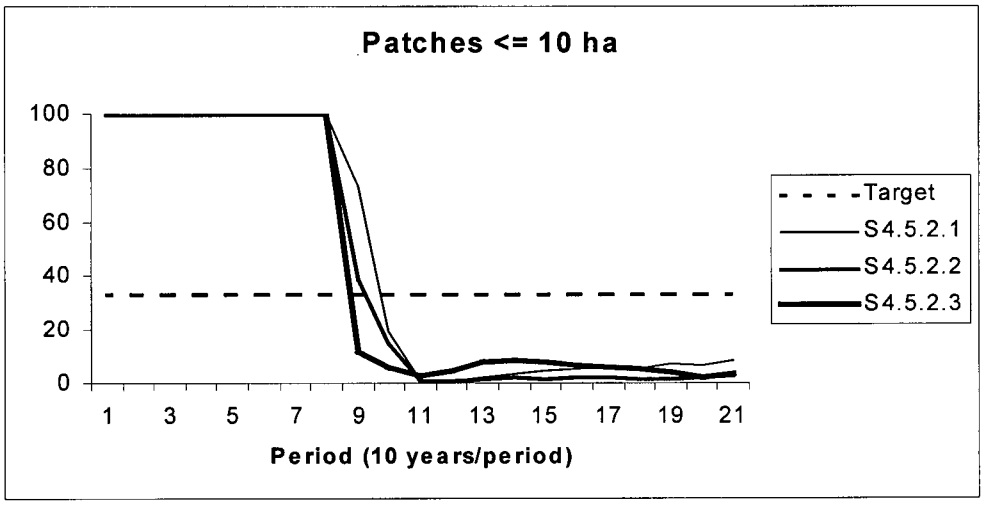
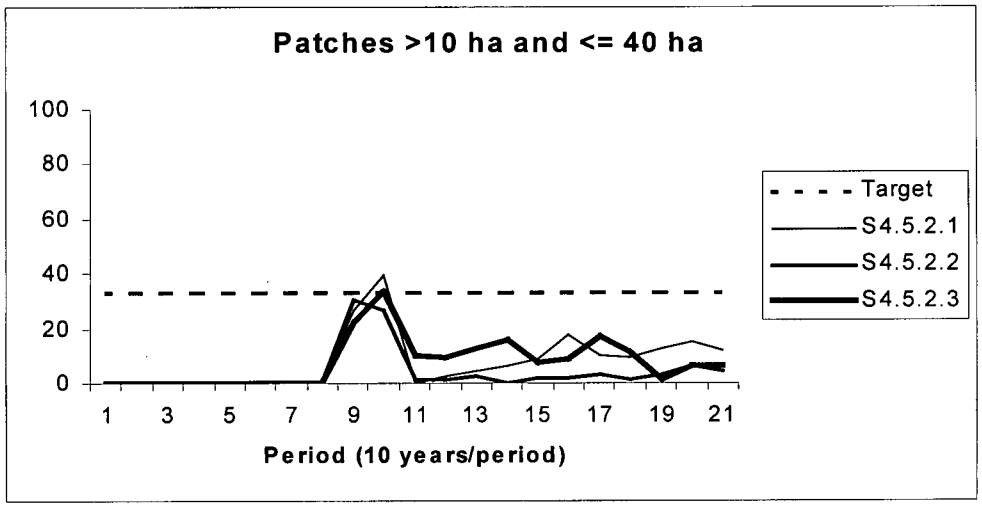


Figure 4.49 - Old (>=100 years) stands for FSOS scenarios S4.5.2.1, S4.5.2.2, and S4.5.2.3.





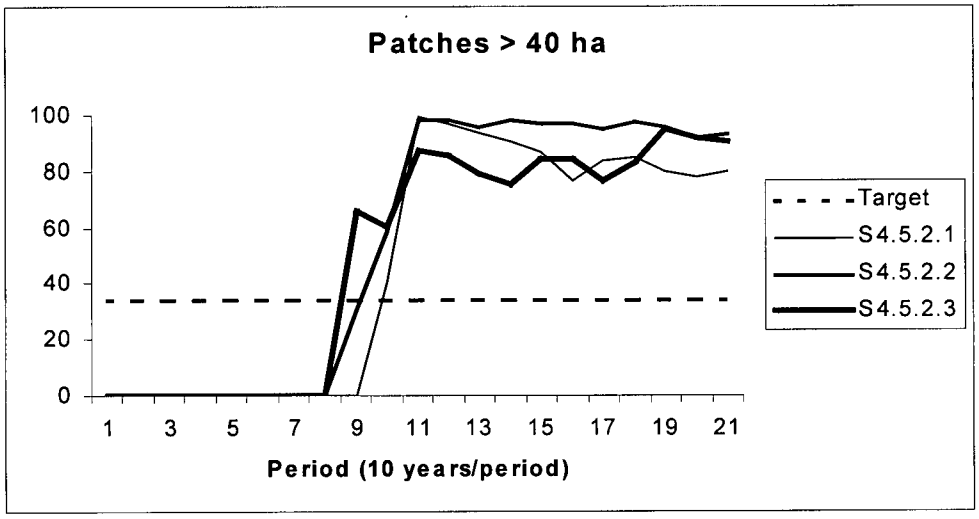


Figure 4.50 - Old (>=100 years) patches for FSOS scenarios S4.5.2.1, S4.5.2.2, and S4.5.2.3.

Figures 4.51, 4.52, and 4.53 show that the desired patterns are achieved in period 10 (year 2100), and maintained for the remainder of the planning horizon. The patterns for the three scenarios are similar because the same targets are used.

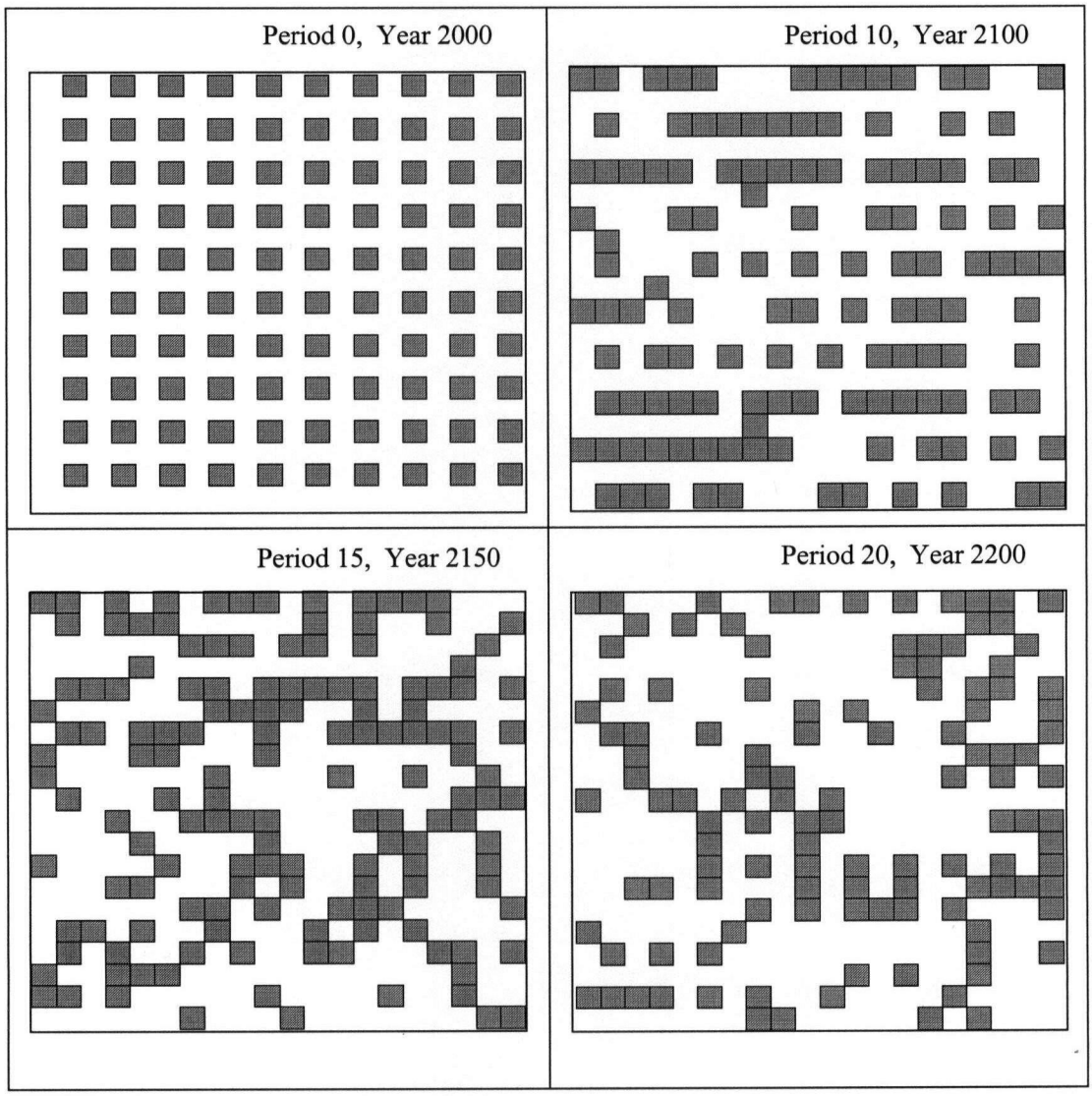


Figure 4.51 - Four snapshots of old patches for FSOS scenario S4.5.2.1.

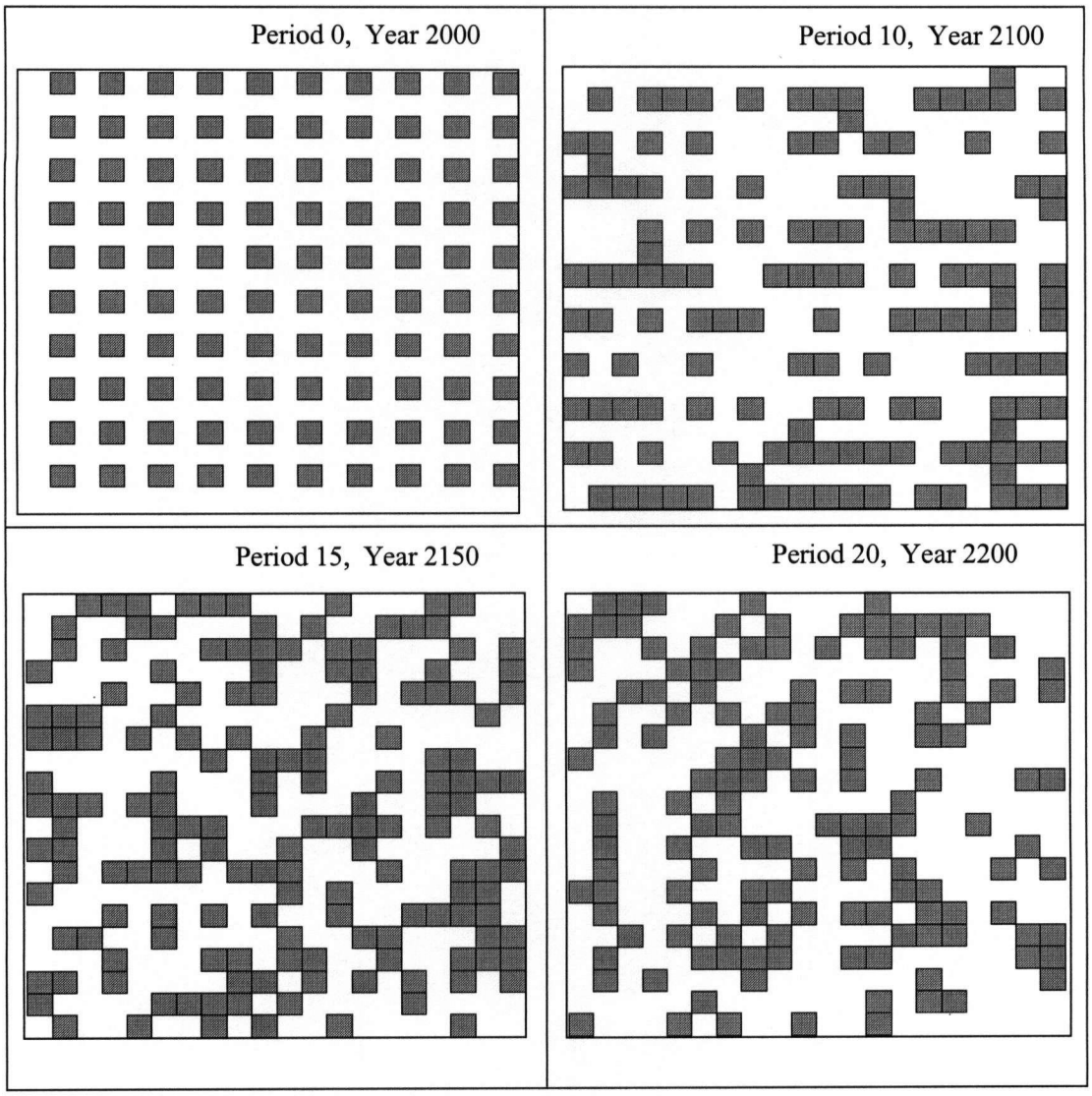


Figure 4.52 - Four snapshots of old patches for FSOS scenario S4.5.2.2.

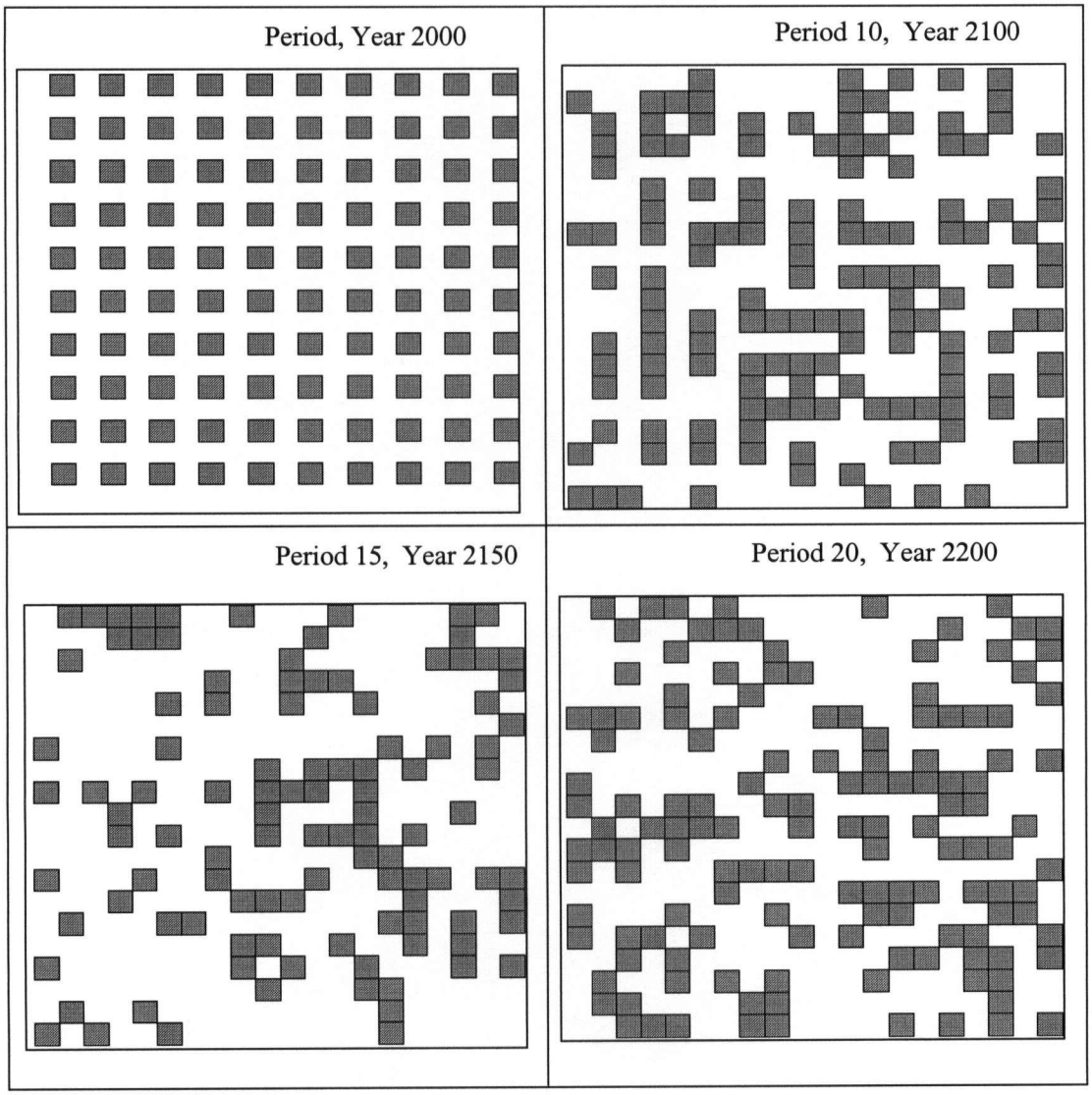


Figure 4.53 - Four snapshots of old patches for FSOS scenario S4.5.2.3.

In all ATLAS runs, no timber production is allowed during the first few decades. It requires 20 years to achieve the maximum young stand targets, and it takes 80 years to achieve the old large patch targets. It is the duty of the analysts to use this information to modify the constraints and re-run the model until acceptable solutions are found. Both desired forest states can be maintained (in the absence of natural disturbance) once they reach the targets.

With FSOS scenario S4.5.2.1, timber flows can be maintained a level that ranges from 18,144 m^3/year to 27,139 m^3/year for the entire planning horizon, however, it requires 90 years to reach the stable old stand requirements, and it depletes an already scarce supply of old stands during periods 1-9. It requires 15 years to reach a maintainable young stand requirement, and it requires 90 years to reach the patch targets (Table 4.12).

Table 4.12 - Summary of ATLAS runs (S4.5.1.1, S4.5.1.2, and S4.5.1.3) and FSOS runs (S4.5.1.1, S4.5.2.2, and S4.5.2.3).

	ATLAS runs			FSOS runs		
Scenario	4.5.1.1	4.5.1.2	4.5.1.3	4.5.2.1	4.5.2.2	4.5.2.3
Average timber (m^3/year)	17,915	18,519	18,504	22,680	20,940	21,074
Maximum timber (m^3/year)	27,730	28,514	25,330	27,139	24,940	31,611
Minimum timber (m^3/year)	0	0	0	18,144	16,668	0
Years to achieve old (>=100 years)target	0	0	0	90	80	0
Years to achieve young (<=20 years) target	10	10	10	15	15	10
Years to achieve large old (>=100 years) patch target	80	80	80	90	85	80

With the FSOS scenario S4.5.2.2, age structure weighting is increased, and the timber flows, on average, are reduced to 20,940 from 22,680 cubic meters per year. Both the old stand targets and old large patch targets can be achieved about 5 years earlier than in scenario S4.5.2.1. However, the depletion of old stands during periods 1-9 is similar to S5.4.2.1. With FSOS scenario S4.5.2.3, the age structure weighting is increased again, and the age structures can be achieved and maintained for the entire planning horizon in a similar

fashion to the ATLAS runs. The timber flows are also similar to the ATLAS runs (Table 4.12).

In summary, FSOS uses weights to manage tradeoffs between forest structure and timber flows, while ATLAS relies on explicit interventions of the analysts to adjust constraints in order to make similar tradeoffs.

Chapter 5

Case Study

The Forest Simulation Optimization System was used on Tree Farm License (TFL) #3 (Slocan Forest Product Limited, 1998). TFL 3 is located in the Nelson Forest Region (Arrow Forest District) near the village of Slocan, B.C. (Figure 5.1 – tenure map). The TFL is located predominantly within the Interior Cedar Hemlock (ICH), Engelmann Spruce – Subalpine Fir (ESSF) and Alpine Tundra (AT) biogeoclimatic zones. The total area of the TFL is 79,796 hectares, with forested, operable and inoperable areas listed in Table 5.1.

The forest industry is an important sector, providing long-term social and economic development in the region. Slocan Forest Product (SFP) is the largest employer in the Slocan Valley and has a significant economic impact not only in the Slocan Valley, but throughout the West Kootenay region.

Currently, it is difficult for SFP to harvest timber because different groups have conflicting interests. To accommodate the concerns of all interest groups, SFP asked experts in relevant fields to clearly define the desired forest structures (age structure + patches) required to sustain non-timber resources within the TFL. FSOS was used to develop a 20-year harvest plan based on these long-term management objectives. The forest transitions projected by FSOS were analyzed by monitoring timber flows and forest conditions. Comparisons between the achieved values and the desired values were made.

ARROW FOREST DISTRICT

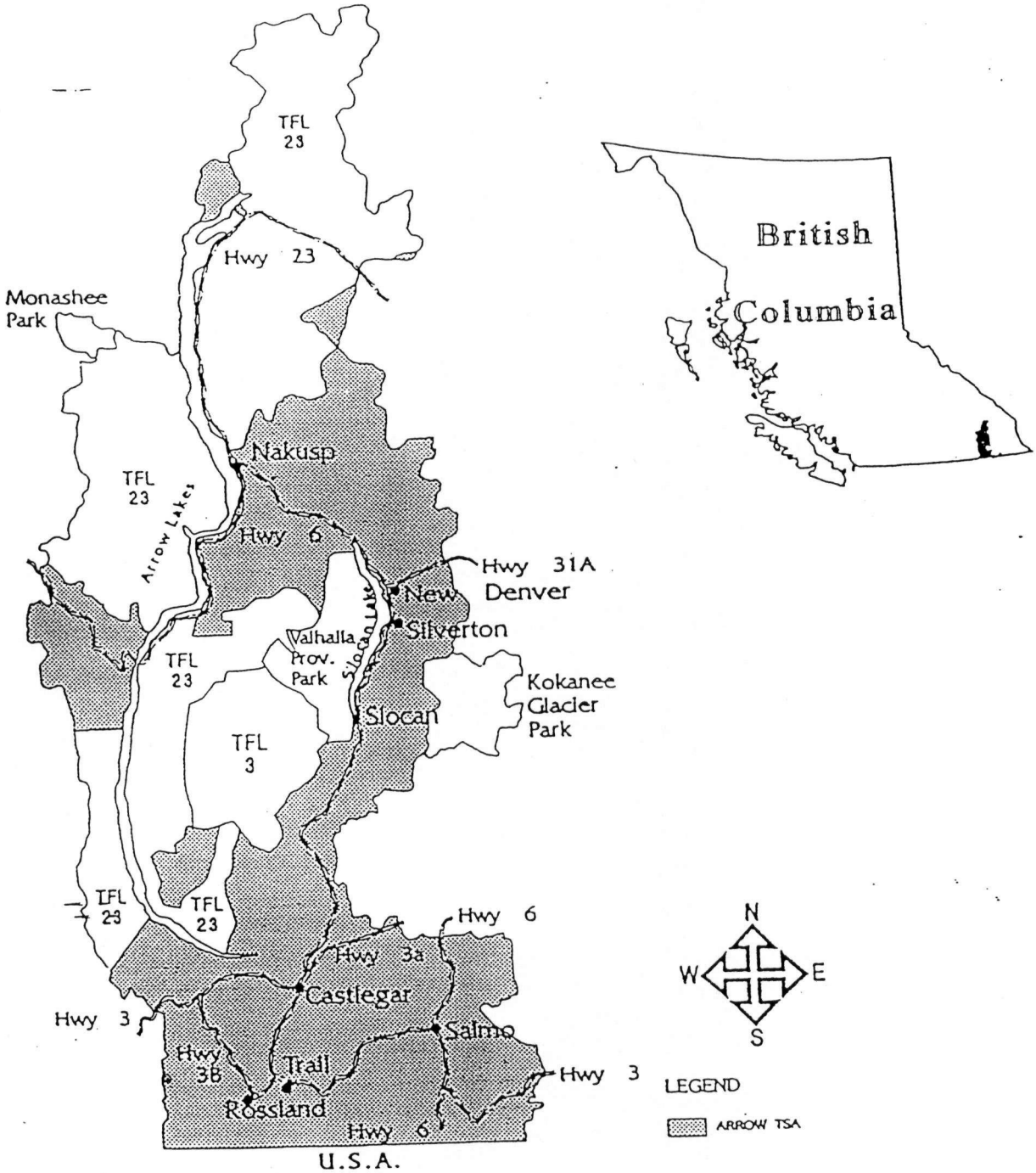


Figure 5.1 - TFL3 tenure map.

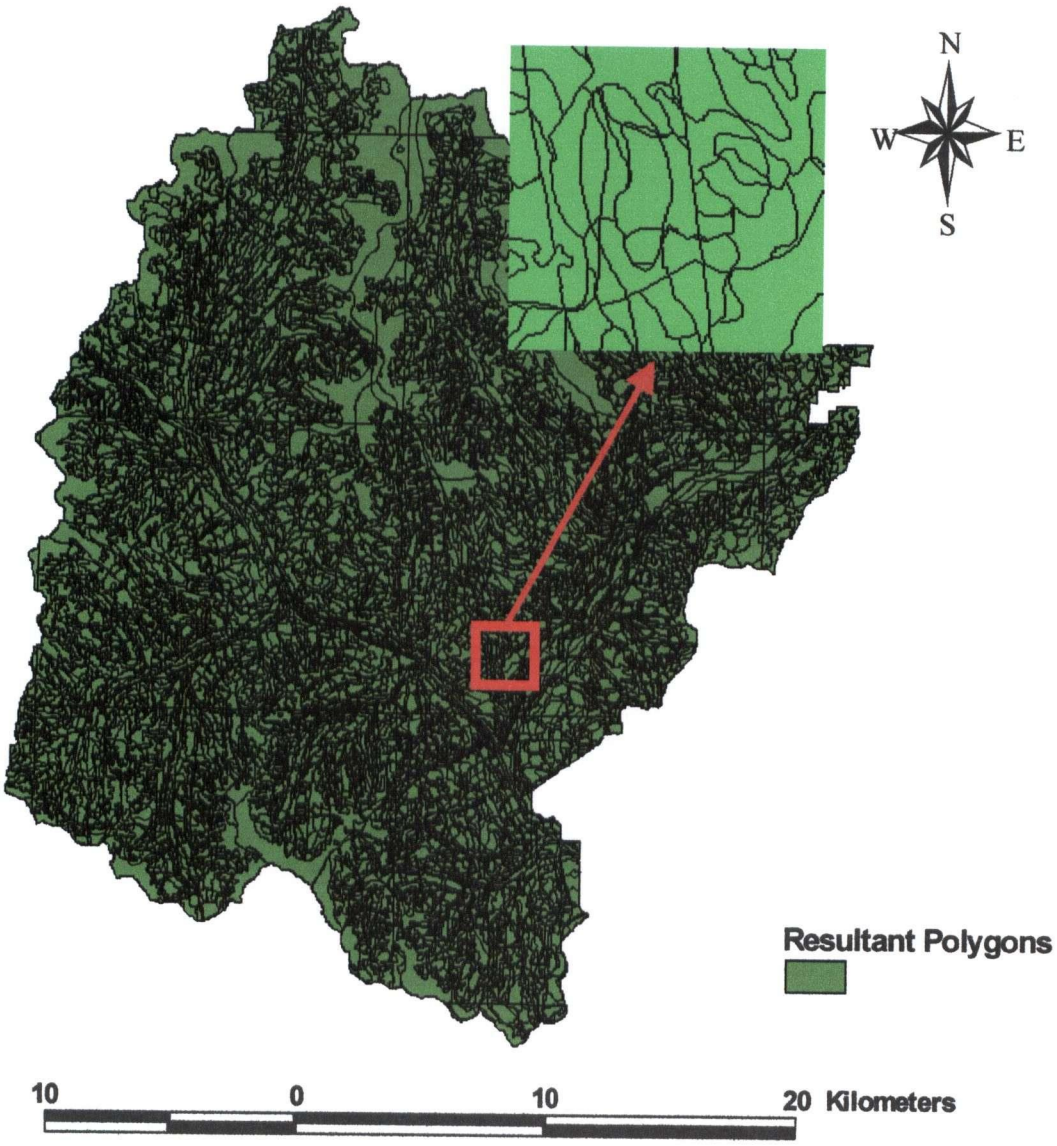


Figure 5.2 – Resultant polygons in TFL #3.

Overlaying the resource layers (Table 5.2) and forest cover generated 17,642 resultant polygons (Figure 5.2).

Table 5. 1 - Summary of TFL #3 area.

	Area (hectares)	% of TFL Area
TFL#3	79,796	100
Total Forest	60,174	75.4
Operable Forest	35,585	44.6
Inoperable Forest	24,589	30.8

The FSOS results are also compared with the ATLAS model by using the FSOS targets as constraints. Sensitivity analyses are used to determine the response of forest structure and timber flows to changes in objective weights in FSOS runs.

The rest of this chapter will be divided into four sections. Section 5.1 describes the resource layers, and the desired states; section 5.2 states the harvest criteria; section 5.3 provides the objective weighting scenarios; and section 5.4 contains the results and discussion.

5.1 Management Layers and Their Objectives

There are 46 layers in this case study (Table 5.2) and each layer has a desired state in terms of age structures and patch size distributions. The most complicated layers are natural disturbance type layers, which require both age structures and patch size distributions. The 46 layers combined with the forest cover layer created 18,000 resultant polygons. A 200-year planning horizon with forty 5-year periods was used. The current and desired states of these layers will be described in the subsequent sections.

Table 5.2 - Resource Emphasis Layers.

Layer ID	Name	Area (ha)
1	Connectivity	11,608
2	VQO Retention	1,894
3	VQO Partial Retention	4,269
5	VQO Maximum Modification	152
6	VQO Modification	4,559
7	Small Business	1,909
8	Robertson Face Watershed	170
9	Airy Face Watershed	577
10	South Tedesco Watershed	220
11	Talbot Watershed	221
12	East Little Slocan Watershed	455
13	Airy/Slocan Residual Watershed	1,411
14	Airy 31.3A Watershed	1,837
15	Airy 31.3B Watershed	278
16	Airy 31.3C Watershed	343
17	Airy 31.3D Watershed	463
18	Airy 31.3E Watershed	328
19	Airy 31.3F Watershed	996
20	Airy 31.3G Watershed	318
21	NDT1 Landscape Unit A16	19,363
22	NDT1 Landscape Unit A17	3,542
23	NDT1 Landscape Unit A36	14,213
24	NDT2 Landscape Unit A16	12,746
26	NDT2 Landscape Unit A36	9,194
27	NDT3 Landscape Unit A16	1,599
28	NDT3 Landscape Unit A17	11,796
29	NDT3 Landscape Unit A36	6,453
51	Bannock Burn non-domestic watershed	3,840
52	Cougar non-domestic watershed	1,630
53	Dago non-domestic watershed	1,287
54	Greasybill non-domestic watershed	4,133
55	Heimdal non-domestic watershed	1,519
56	Hoder non-domestic watershed	6,734
57	Koch Residual non-domestic watershed	4,022
58	Lower Grizzly non-domestic watershed	2,214
59	Lower LS Residual non-domestic watershed	3,914
60	Ludlow non-domestic watershed	2,051
61	Mista non-domestic watershed	1,079
62	Russel non-domestic watershed	3,059
63	Slocan Lake non-domestic watershed	160
64	Upper Grizzly non-domestic watershed	3,074
65	Upper Koch Residual non-domestic	5,818
66	Upper LS Residual non-domestic watershed	4,625
67	Woden non-domestic watershed	4,207

5.1.1 Visual Quality Objectives (VQOs)

There are 4 levels of visual quality objectives (Figure 5.3). Age class structure percentage targets for VQOs are defined in Table 5.3.

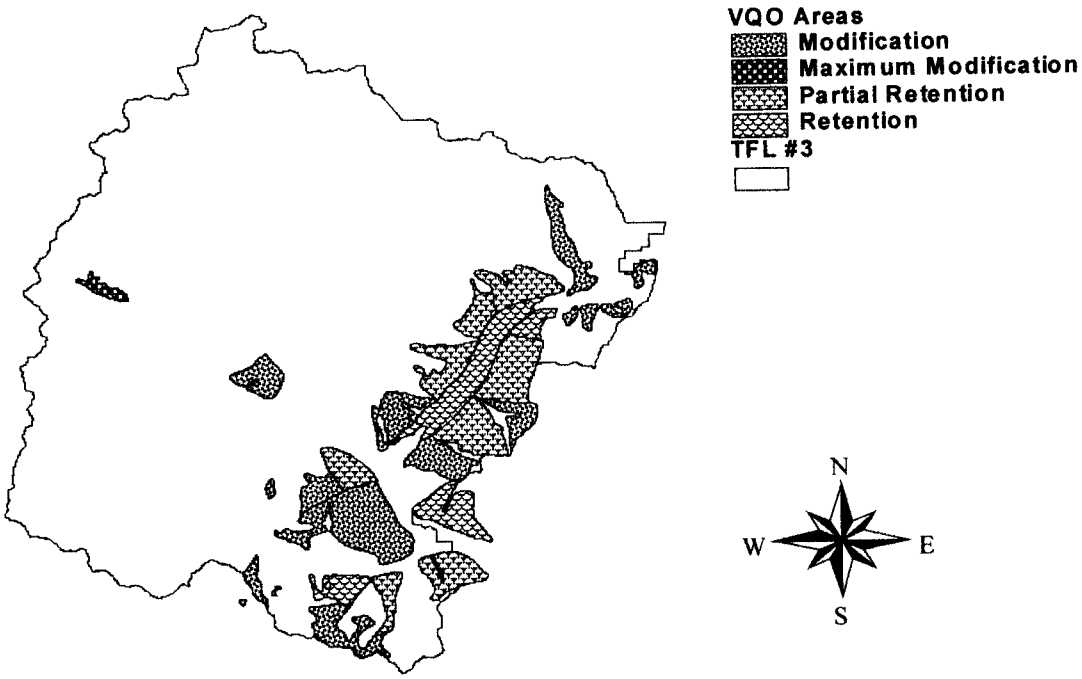


Figure 5.3 – Visual Quality Objective areas in TFL #3.

Table 5.3 - Visual quality objectives (VQO)

Layer ID	VQO Levels	Forested Area	Operable Area	% (< 25 years)	
				Current	Maximum Target
2	Retention	1,894	829	6	5
3	Partial Retention	4,269	2,625	5	15
5	Modification	4,559	3,267	12	25
6	Maximum modification	152	15	0	40

5.1.2 Caribou Connectivity Corridors

The caribou connectivity corridor (Figure 5.4) has 2,675 polygons and covers 11,608 hectares of which 5,087 hectares are operable. The mature stand target for the corridor is a minimum of 70% older than 100 years, however, the current state is only 49.5% older than 100 years.

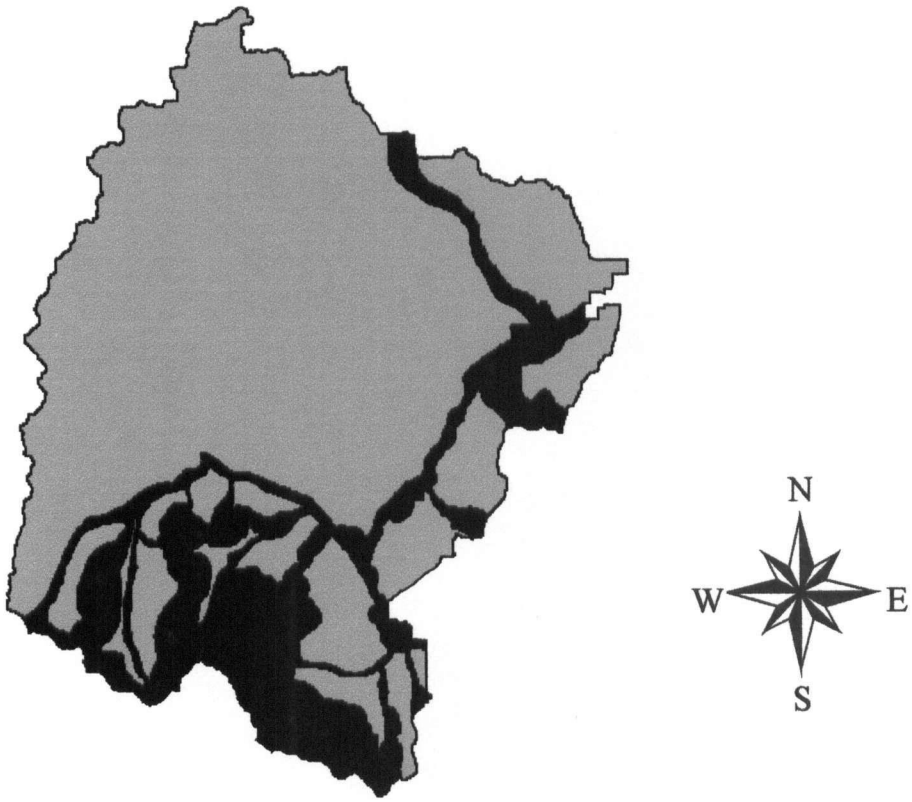


Figure 5.4 - Caribou Connectivity Corridors.

5.1.3 Wildlife Trees (Stand-level Biodiversity)

Wildlife tree retention was accounted for through a percentage netdown applied to each block. Approximately 50% of the wildlife tree retention objective will be met through riparian management areas and inoperable areas; therefore, initial wildlife tree requirements have been reduced. The percentage reductions are in Table 5.4.

Table 5.4 - Wildlife tree reserve percentages.

Layer ID	Landscape Unit	NDT*	Biodiversity Emphasis	Forest Area	Operable Area	Wildlife tree reduction (%)
21	16	1	Low	19,363	10,114	2
24	16	2	Low	12,746	11,426	2
27	16	3	Low	1,599	1,420	2
22	17	1	Intermediate	3,542	1,981	2
25	17	2	Intermediate	0	0	2
28	17	3	Intermediate	11,796	2,616	3
23	36	1	Low	14,232	3,632	2
26	36	2	Low	9,194	3,767	2
29	36	3	Low	6,453	1,630	2

*NDT is Natural Disturbance Type (Biodiversity Guidebook, MOF, 1995)
1 = ecosystems with rare stand-initiating events
2 = ecosystems with infrequent stand-initiating events
3 = ecosystems with frequent stand-initiating events

5.1.4 Landscape-level Biodiversity

There 4 biogeoclimatic zones in TFL #3 (Figure 5.5). Age class structure targets are applied to individual Natural Disturbance Types (NDTs) based on the biodiversity emphasis options (Table 5.5).

- The young stand age for all NDTs is <= 40 years;
- the mature stand age for NDT 1 is >40 and <=120 years, for NDT 2 and 3 it is >40 and <=100 years; and
- the old stand age for NDT 1 and 2 is >250, for NDT 3 is >140.

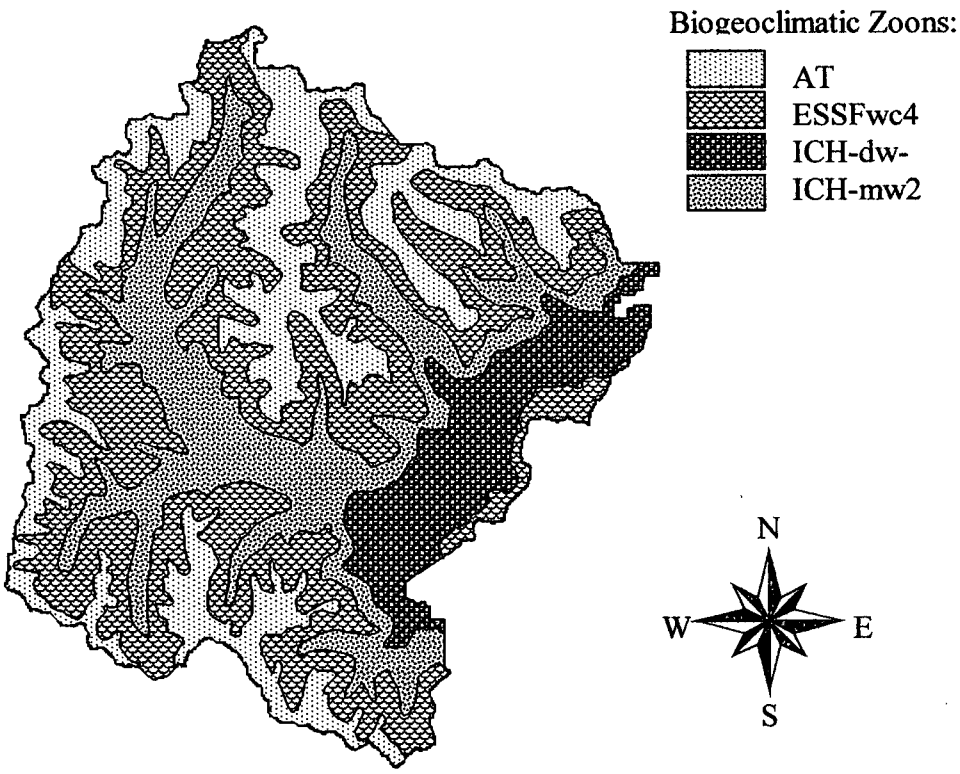


Figure 5.5 - Biogeoclimatic zones in TFL #3.

Table 5.5 - Biodiversity age class structure targets and current states.

Landscape Unit	NDT	Biodiversity Emphasis	Young Stand (%)		Mature Stand (%)		Old Stand (%)	
			Current	Target	Current	Target	Current	Target
16	1	Low	14.4	36	41.8	-	9.6	19*
16	2	Low	13.6	36	22.4	-	12.8	9
16	3	Low	20.6	36	16.9	-	8.4	14*
17	1	Intermediate	1.4	22	44.4	22	4.2	19*
17	3	Intermediate	7.8	22	24.2	9	7.5	14*
36	1	Low	12.2	36	56.2	-	4.1	19*
36	2	Low	11.8	36	29.3	-	3.0	9*
36	3	Low	4.2	36	28.2	-	5.2	14*

* = currently does not meet target.

Patch size distribution percentage targets for each NDT are assigned according to *Biodiversity Guidebook* by MOF, 1995 (Table 5.6).

Table 5.6 - Patch size distribution targets for young and old stands.

Layer ID	Landscape Unit	NDT	Biodiversity Emphasis	% Area of 0-40 ha patch targets	% Area of 41-80 ha patch targets	% Area of 81-150 ha patch targets
21	16	1	Low	35	35	30
24	16	2	Low	35	35	30
27	16	3	Low	25	35	40
22	17	1	Intermediate	35	35	30
25	17	2	Intermediate	35	35	30
28	17	3	Intermediate	25	25	40
23	36	1	Low	35	35	30
26	36	2	Low	35	35	30
29	36	3	Low	25	35	40

5.1.5 Riparian Zones

Riparian zones were excluded from the harvestable land base. However, they still contribute to age class structure and patch size distribution targets.

5.1.6 Watersheds

There are 30 watersheds in TFL 3 (Figure 5.6 and Table 5.7). Age structure rules were applied to watersheds based on their respective equivalent clear cut area (ECA) and the age to reach a 9 m hydrological green-up. With a 30% ECA applied, the age structure target is a maximum of 30% of the watershed area in stands, which are 35 years or younger (time for stands to reach 9 meters).

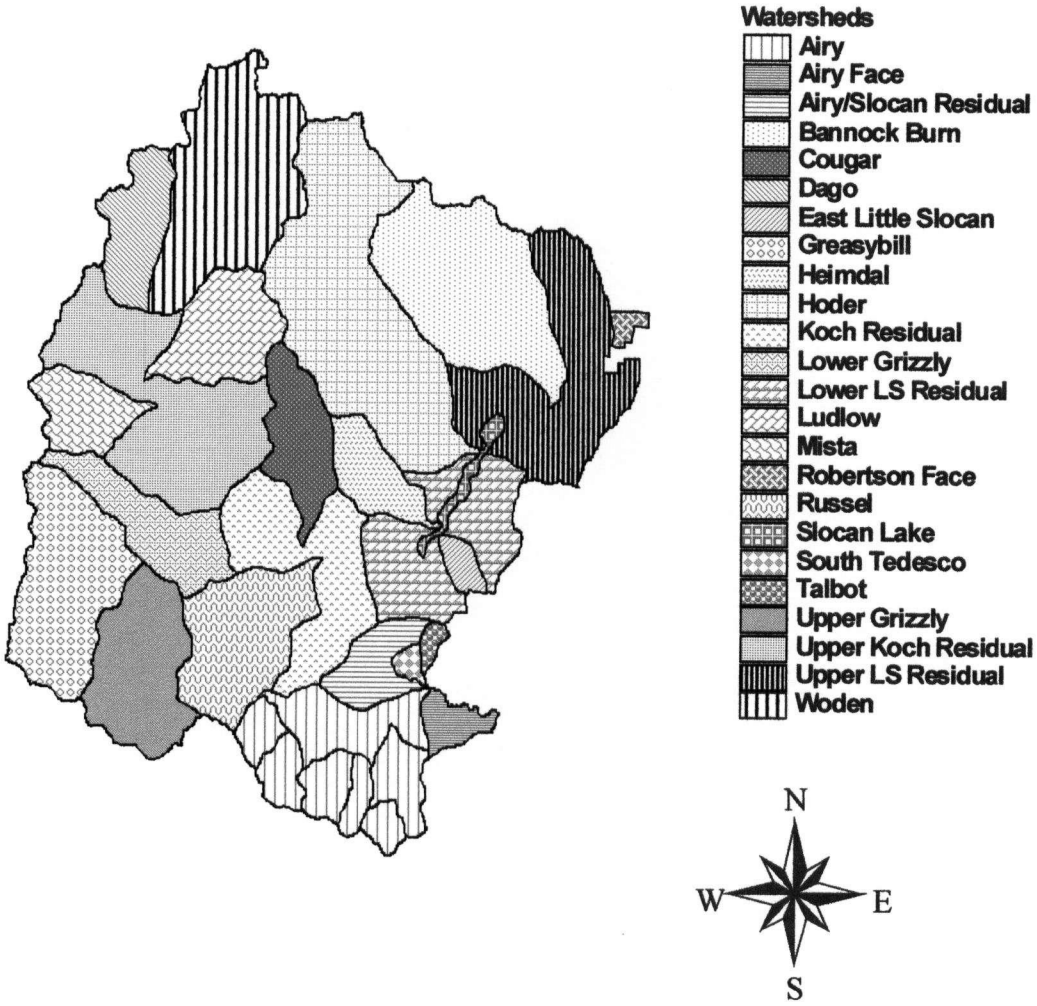


Figure 5.6 - Watersheds in TFL #3.

Table 5.7 - Watershed young stand (<=35 years) targets and current states.

Layer ID	Watershed Name	Upper Bound(%)	Current(%)
8	Robertson Face Watershed	30	0
9	Airy Face Watershed	20	15
10	South Tedesco Watershed	30	9
11	Talbot Watershed	30	0
12	East Little Slocan Watershed	30	6
13	Airy/Slocan Residual Watershed	20	25
14	Airy 31.3A Watershed	20	18
15	Airy 31.3B Watershed	20	24*
16	Airy 31.3C Watershed	20	26*
17	Airy 31.3D Watershed	20	28*
18	Airy 31.3E Watershed	20	40*
19	Airy 31.3F Watershed	20	31*
20	Airy 31.3G Watershed	20	33*
51	Bannock Burn non-domestic watershed	35	14
52	Cougar non-domestic watershed	35	10
53	Dago non-domestic watershed	35	10
54	Greasybill non-domestic watershed	35	11
55	Heimdal non-domestic watershed	35	44*
56	Hoder non-domestic watershed	35	17
57	Koch Residual non-domestic watershed	35	13
58	Lower Grizzly non-domestic watershed	35	2
59	Lower LS Residual non-domestic watershed	35	16
60	Ludlow non-domestic watershed	35	7
61	Mista non-domestic watershed	35	1
62	Russel non-domestic watershed	35	5
63	Slocan Lake non-domestic watershed	35	2
64	Upper Grizzly non-domestic watershed	35	13
65	Upper Koch Residual non-domestic watershed	35	10
66	Upper LS Residual non-domestic watershed	35	4
67	Woden non-domestic watershed	35	10

* = currently does not meet target.

5.2 Harvest Criteria

The first five years of harvest are fixed according to Slocan Forest Product's 5-year forest development plan. Resultant polygons generated by GIS overlays are used as the basic planning units. Resultant polygons are amalgamated to create openings; and the openings then aggregate over time to

create patches. Stand-level growth and yield curves were generated with the growth and yield models VDYP (Variable Density Yield Program) for natural stands and TIPSY (Table Interpolation Program for Stand Yield) for managed stands.

5.3 Objective Weightings

Weighting of the objectives and parameters is a key process in the operation of the model, and the choice of weighting is specific to the forest being modeled. Table 5.8 shows the weighting used in this analysis (3 scenarios). The absolute value of the weights is not relevant, rather, the weightings show the relative importance of each parameter (i.e. in scenario S5.2, patch size distribution is 1.6 times more important than total volume flow). Generally, the higher the weighting, the sooner the target can be achieved. The weightings are only control parameters, and they depend on the difficulty of achieving the targets within time limits. By placing a high priority on biodiversity objectives, a relatively higher importance is attributed to patch size and age class structure objectives. Low weight was applied to the even volume flow parameter because it is an easy target to achieve. A cut block size objective was added to control cut block size. The block size range can be specified for each layer; and the block size must meet the requirements of all the layers that share the block. A high weight was given to the cut block size because it proved to be a different target to achieve.

Table 5.8 - Weighting parameters.

Parameters	Weight			
	Scenario S5.1	Scenario S5.2	Scenario S5.3	Atlas
Total volume	1	1	1	--
Patch size distribution	16	1.6	0.16	--
Age class structure	15	1.5	0.15	--
Even volume flow	0.2	0.2	0.2	--
Cut block size	20	2	0.2	--

5.4 Results and Discussions

Figure 5.7 shows the performance of the objective function values for weighting Scenario S5.2 (1 million iterations). Performances for other scenarios are similar to Scenario S5.2. In Figure 5.7, "Total Obj" is the total objective function value; "Total Timber" is the total timber volume produced over the planning horizon; "Patch Size" is the patch size distribution penalty; "Age Class" is the age class structure penalty; "Block Size" is the cut block size penalty; and "Timber Flows" is the timber even flow penalty.

All objective function indicators continue to improve as the number of iterations increases until further iterations do not yield significant improvements. When the indicators level off, a good solution has been achieved. Table 5.9 gives the solution time with a Pentium 266 MHZ and 98 MB RAM computer.

Table 5.9 – Solution Times.

Iterations	200,000	400,000	600,000	8,00,000	1,000,000
% of the best solution	32.5	72.4	91.3	98.8	100
Time (hour)	1.8	3.5	5.3	7.2	8.8

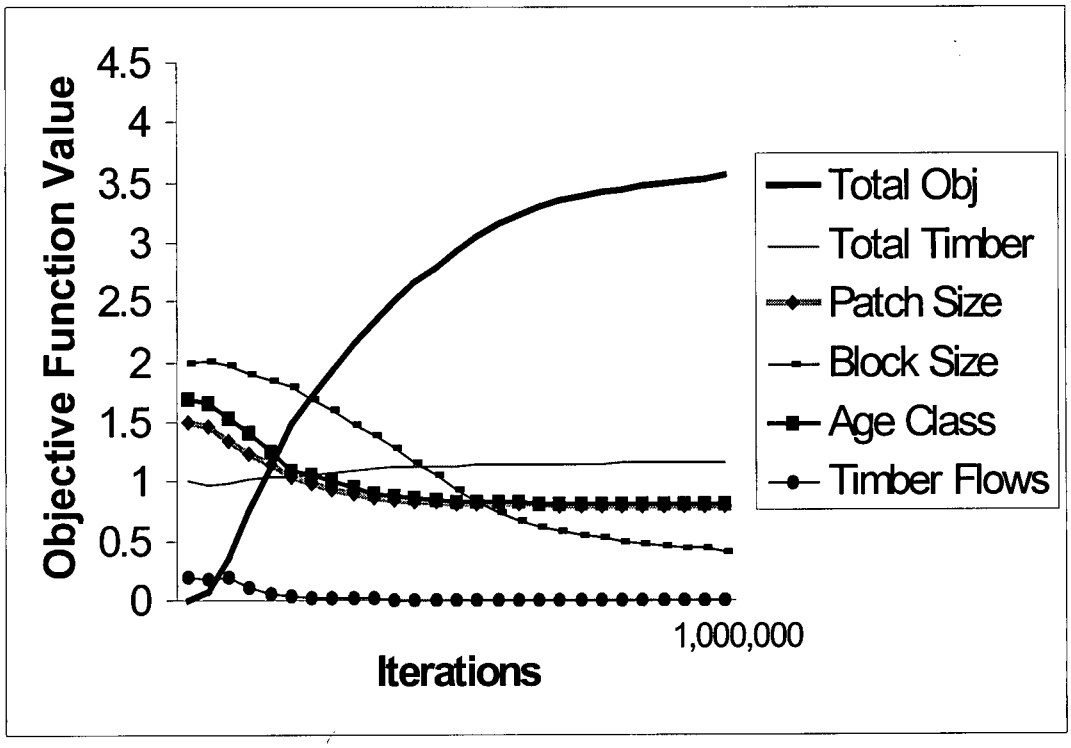


Figure 5.7 – Objective function values for Scenario S5.2 over 1 million iterations.

Figure 5.8 shows the 20-year plan harvest blocks. The minimum cutblock size target was set at 10 hectares. Results show that the average size is greater than the minimum desired cutblock size (Figure 5.9), and that less than 10% of the cut blocks in number, or 2% by area, in all periods are smaller than 10 hectares.

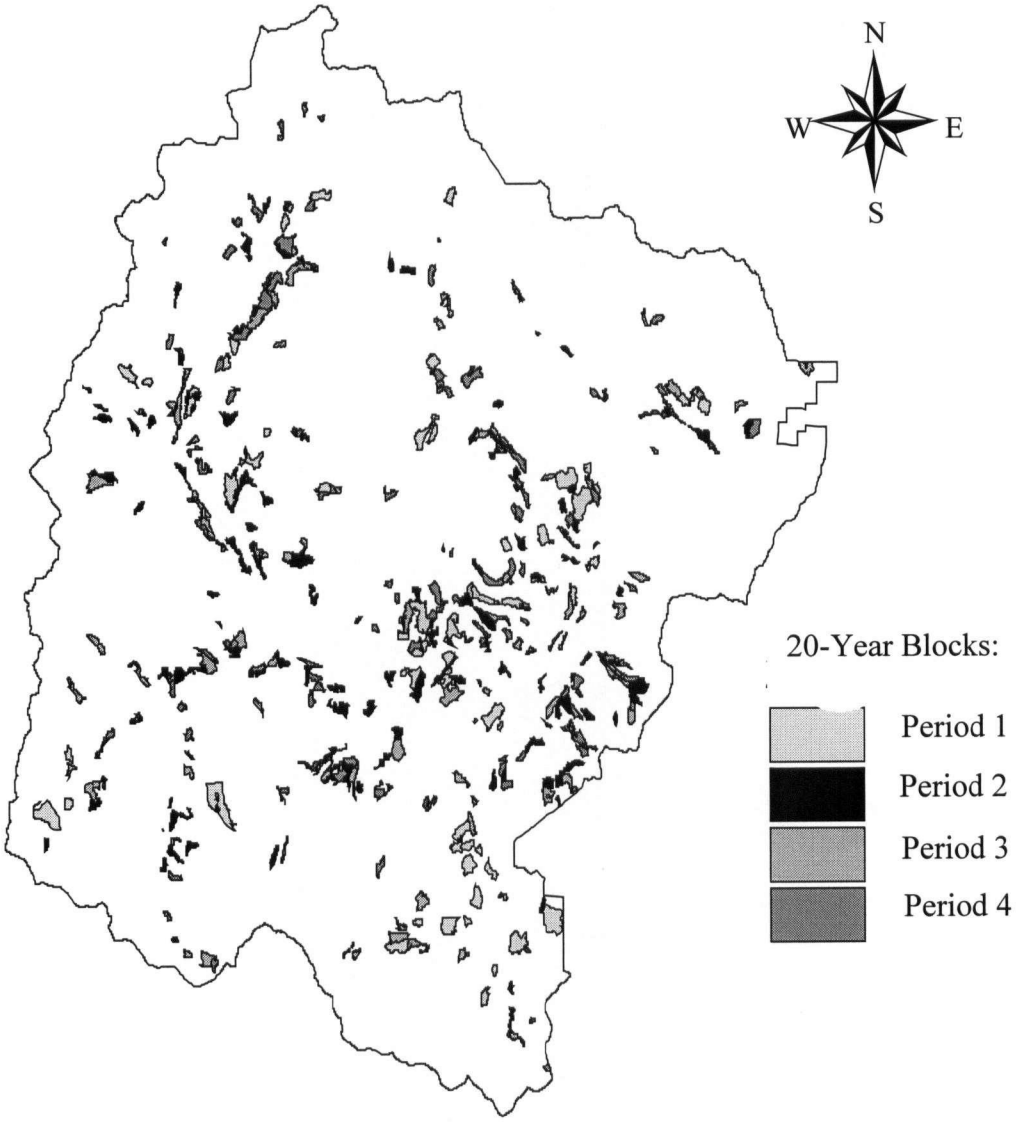


Figure 5.8 – Harvest blocks for 20 years (by 5-year period).

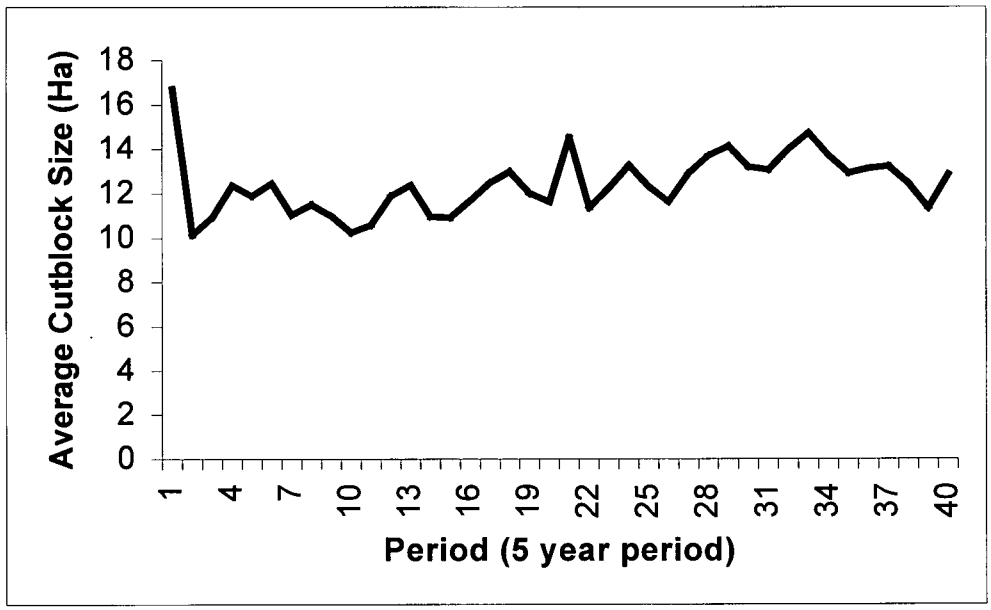


Figure 5.9 - Average cut block size over all periods.

5.4.1 Timber Flows

Figure 5.10 shows the timber flows for three FSOS runs and an ATLAS run. In Scenario S5.1, timber has the lowest weighting compared with scenarios 2 and 3, and it has the lowest timber flows (Figure 5.10 and Table 5.10). With Scenario S5.2, over the long-term (200 years), Atlas and FSOS produce almost the same timber flows. However, in the short-term (40 years), FSOS achieved higher volume flows because the lower weightings on age and patch targets allowed it to harvest more. Atlas uses "hard" constraints and if the analyst does not relax them, the timber harvest is seriously limited during the first 40 years.

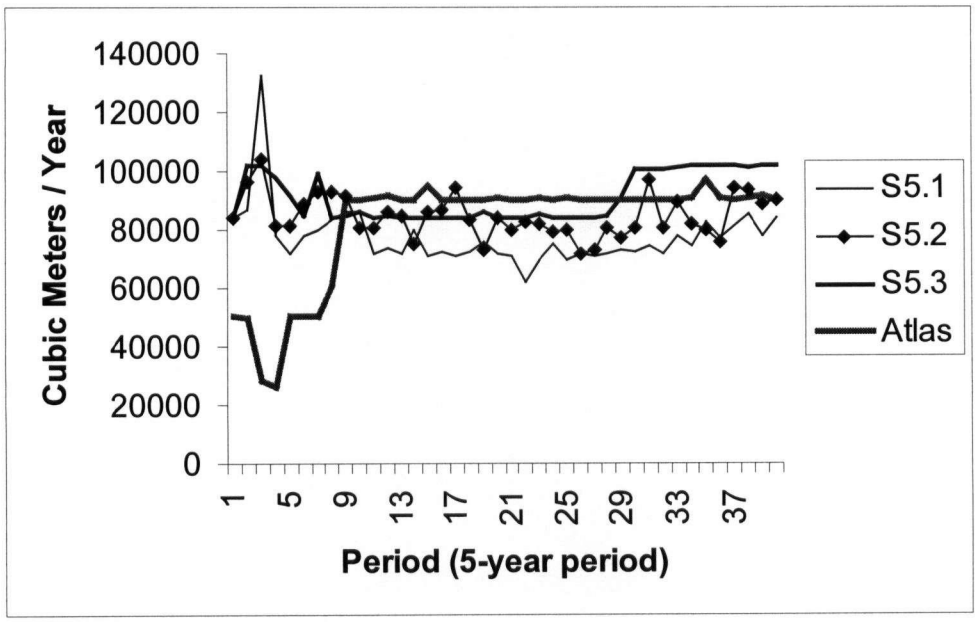


Figure 5.10 - Timber volume flows over all periods.

Table 5.10 - Timber volume flows of TFL #3.

	Scenario S5.1	Scenario S5.2	Scenario S5.3	ATLAS
Average volume flows (m^3 / year)	77,301	84,756	91,145	81,867

Figure 5.10 demonstrates that the timber flows increase after 150 years (30 periods). Two additional runs were conducted with a 400-year planning horizon, which confirmed that the forest reaches a stable state and high timber flows can be maintained after 150 years.

5.4.2 Watersheds

Figure 5.11 demonstrates how the targets are achieved in one typical watershed over time. The maximum allowable young stand target (<35 years) is 20%. The spikes at periods 3 and 4 are caused by a large amount of stands which have to be harvested to meet patch target and/or age structure targets. With Scenario S5.3, timber has the highest weighting and age class structure has the lowest weighting. The achieved age class structure is close to the target. With Scenario S5.1, where timber has the lowest weighting and age class structure has the highest weighting, the achieved age class structure is far below the target. The targets for other watersheds are achieved within a number of periods, depending on the current state.

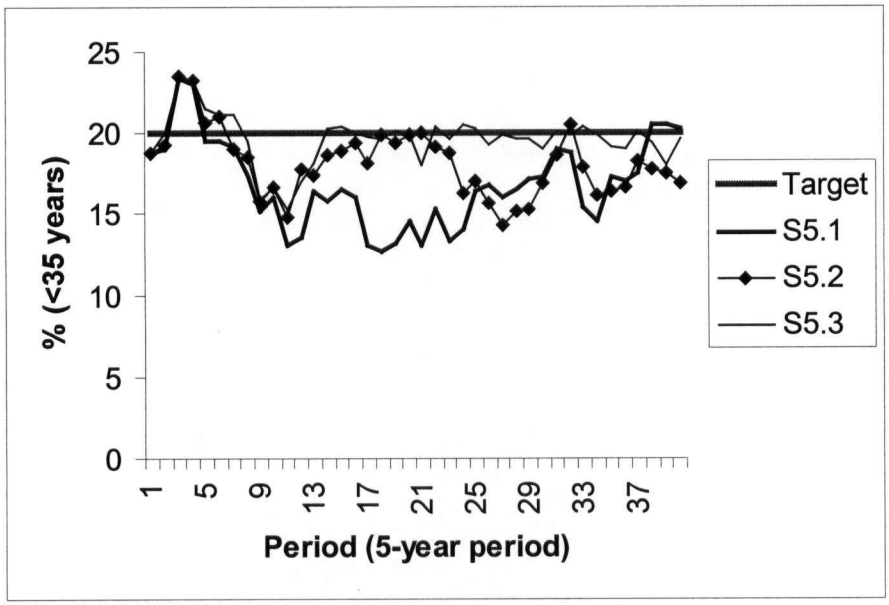


Figure 5.11 - Young (<35 years) stands of Airy 31.3D watershed.

5.4.3 Visuals

Figure 5.12 presents an example of how visual resource objectives are achieved and maintained over time. With Scenario S5.3, timber has the highest weighting and age class structure has the lowest weighting; so the achieved age class structure is close to the target (10% tolerance). With Scenario S5.1, where timber has the lowest weighting and age class structure has the highest weighting, the achieved age class structure is farther below the target.

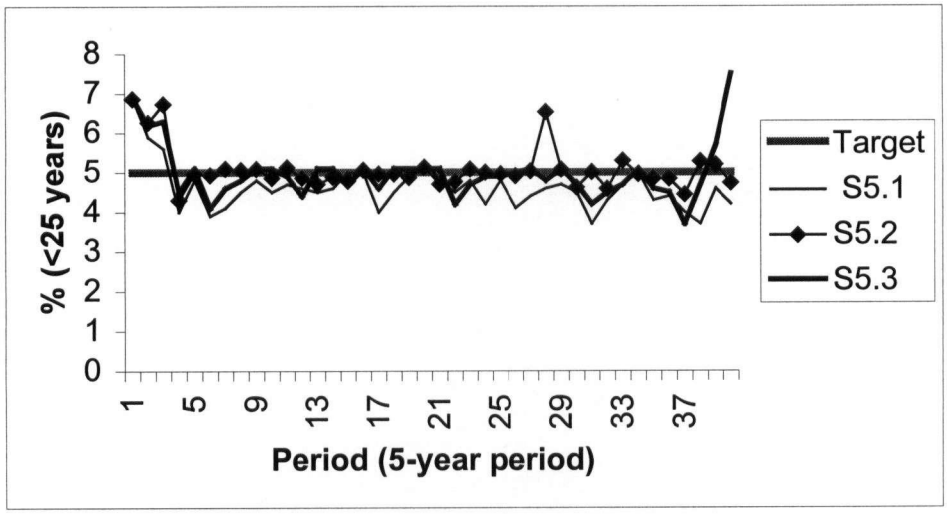


Figure 5.12 - Young (<20 years) stands of VQO retention area.

5.4.4 Natural Disturbance Type and Biodiversity

Figure 5.13 shows the old (>250 years) stand percentage targets achieved in a NDT1 area of landscape unit 16 during each period. The old stand targets for NDT 1 of landscape unit 16 are met in 60 years. In this specific case, a surplus of old stands develops because natural disturbance is not considered

and the inoperable stands are aging. The inoperable area alone is sufficient for the old stand target, so the weight has almost no effect on the results.

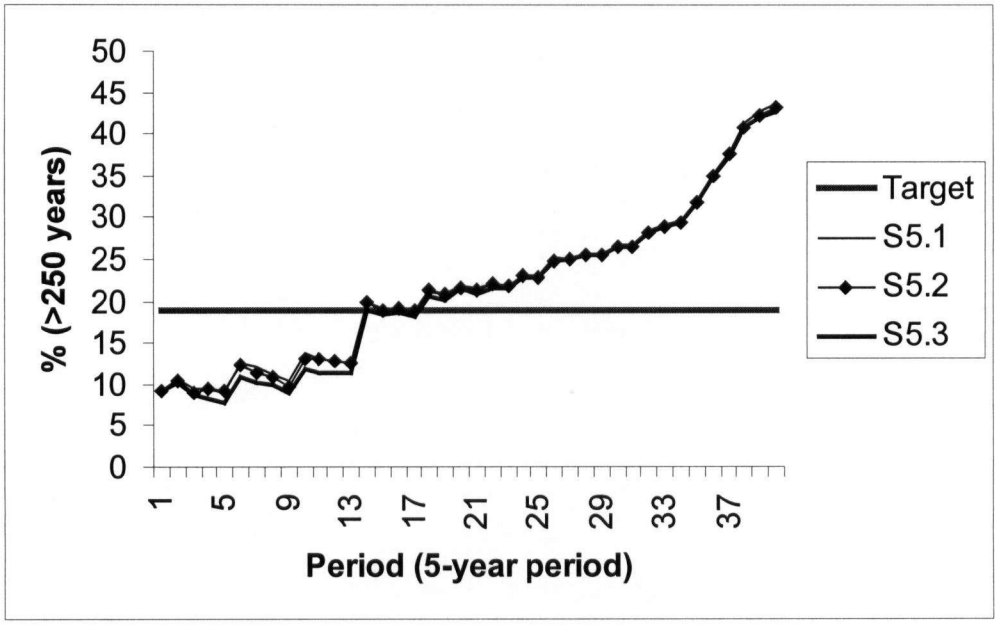


Figure 5.13 - Old (>250 years) stands of NDT1, landscape unit 16.

Figures 5.14 (A1 – B4) show the achieved and desired patch size distributions for NDT1 of landscape unit 16. Graphs A1 – A4 are for young stands and graph B1 – B4 are for old stands. The targets for the smaller sized old patches are maximum targets, whereas the targets for smaller sized young patches are minimum targets. The target percentages of small sized patches for young and old stands are the same (35%, Figure 5.14 A1 and B1). However, fewer small old patches are desired, whereas more small young patches are desired.

The targets for the large-size (>250 hectares) old (>250 years) patches are minimum targets, whereas the targets for the larger sized young patches are maximum targets. The percentages of large (>250 ha) patches for young and old stands can be 0% (A3, B3, A4 and B4). However, more large old patches are desired, whereas less large young patches are desired. Some large (>250 ha) young (<=40 years) patches are created around period 6 (Figure 5.16 and Figure 5.14 A4) because these stands are "over mature" and have to be harvested under the assumptions of the model (stands older than maximum harvest age must be harvested or they will "collapse" and regenerate naturally).

Figure 5.15 and Figure 5.16 show the achieved patch size distributions of old and young stands in NDT1 of landscape unit 16. For the old (>250 years) stands, the percentage of large (>250 hectares) patches is increasing and the percentage of small patches is decreasing over time. For the young (<40 years) stands (Figure 5.16), the percentage of large (>250 hectares) patch size is decreasing and the percentage of small (<40 hectares) patches is increasing over time. This implies that we can build large old patches while harvesting with small openings. A large old patch surplus occurs because the inoperable stands are aging in the absence of natural disturbance.

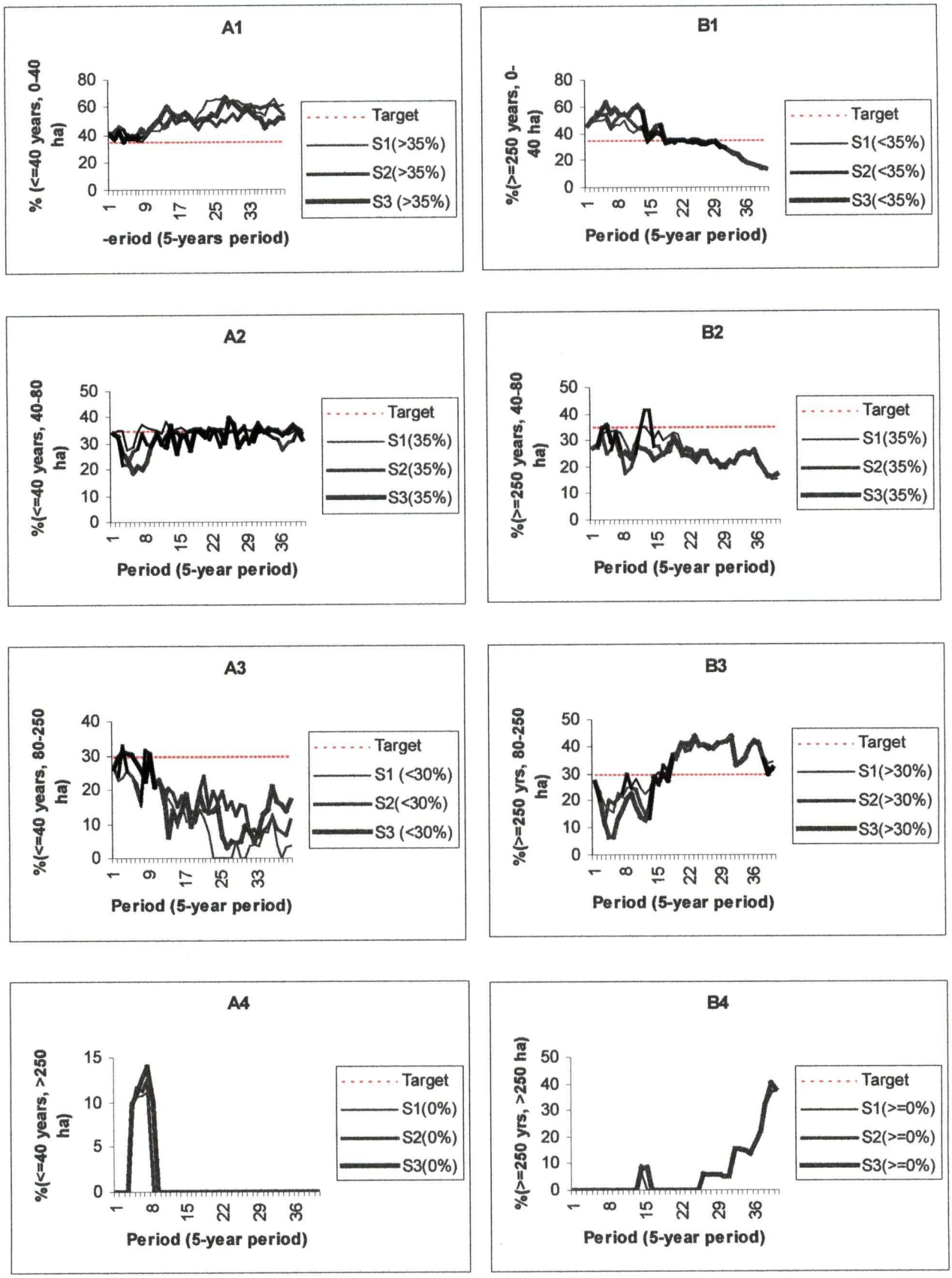


Figure 5.14 – Patch size distribution for NDT 1 of Landscape unit 16

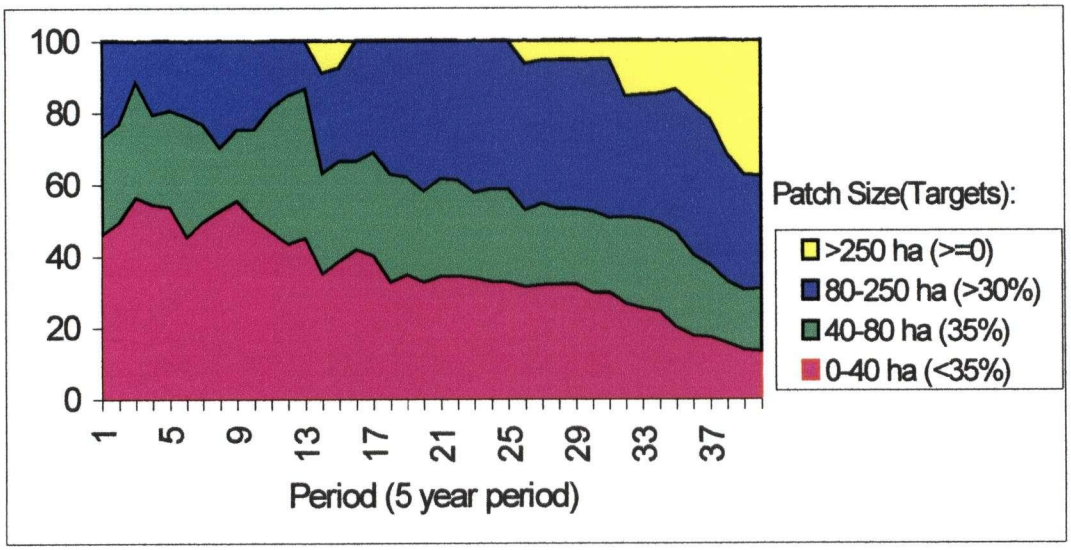


Figure 5.15 - Old (>250 years) patches of NDT1, Landscape Unit 16.

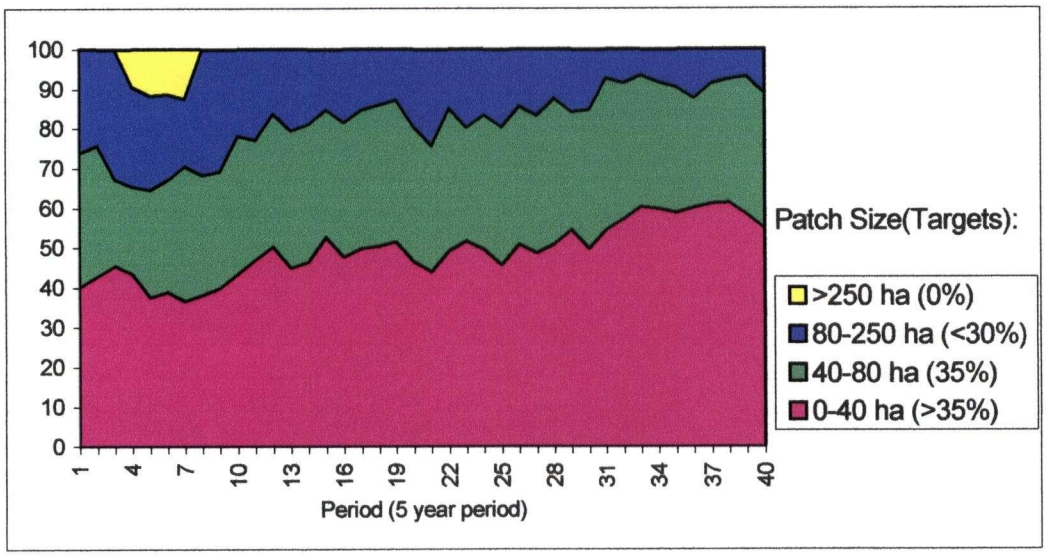


Figure 5.16 - Young (<40 years) patches of NDT1, Landscape Unit 16.

5.4.5 Wildlife Connectivity Corridors

Figure 5.17 shows the mature stand percentage achieved in connectivity corridors during each period. The target is met at period 8 (40 years) and is

maintained over the remaining planning horizon. A surplus occurs because the inoperable stands are aging in the absence of natural disturbance. In all scenarios, no area in the corridor is harvested during the first 8 periods, so the results are insensitive to the weightings.

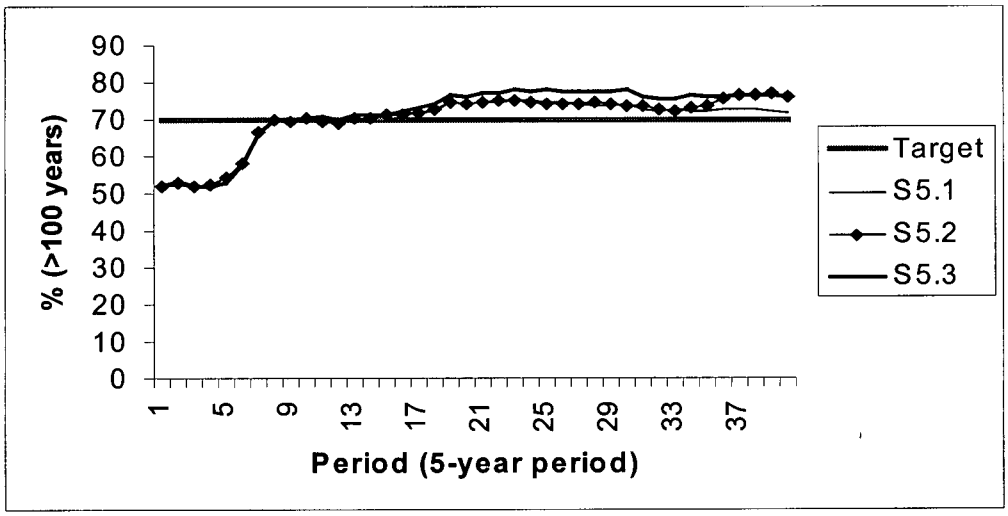


Figure 5.17 – Caribou connectivity corridor mature stands over time.

5.4.6 General Observations

The desired states of all layers can be achieved within 200 years. Some layers are achieved earlier while others are not satisfied until period 15. A stable timber flow is maintained and the impacts of non-timber resources on timber flow are reduced. If these are unacceptable, objective weights should be adjusted and the model re-run.

Chapter 6

Conclusions and Recommendations

Conclusions

A Target-oriented Forest landscape Blocking and Scheduling (TFBS) theory was developed. A tool, the Forest Simulation Optimization System (FSOS) model was built based on the TFBS theory to produce strategies for forest treatment blocking and scheduling while transforming forest landscapes to desired states. A simulated annealing algorithm was used in FSOS to make tradeoffs between conflicting resource values. FSOS was tested on a sample data set and used to prepare a 20-year and 200-year plan for a 80,000 ha Tree Farm in British Columbia.

The conclusions drawn from this study are:

1. The thesis has shown that age-structure and patch-size distributions are effective landscape-level indicators for non-timber resources. By using these two indicators, the forest landscape can be easily measured and monitored.
2. Combining blocking and scheduling is an effective way to achieve and maintain patch size distribution targets over the planning horizon while maximizing timber flows.
3. Sensitivity analysis of the sample data set demonstrates that the TFBS approach can produce strategies to transform forest landscapes from different initial states to the same desired state. It can also identify treatment strategies under different natural disturbance regimes.

4. The case study showed that the TFBS approach integrates the short- and long-term planning processes. It produces a long-term (up to several rotations) treatment schedule according to current states, desired states, projected dynamics and the sustainability of resources. The short-term schedule (1 – 20 years) is a subset of the long-term schedule, which guides current forest operations.
5. FSOS is an efficient tool for adaptive forest management. Forest treatment schedules can be modified when forest engineers reconfigure the blocks, update the database or when natural disturbance occurs.
6. The case study demonstrated that the TFBS approach allows simultaneous planning for multiple layers and multiple rotations. Tradeoffs can be made between resources and between rotations by adjusting objective weights. This differs from time-step simulation, which requires explicit intervention of the analyst to examine tradeoffs between resources and between rotations (or periods).
7. The case study demonstrated that forest management aimed at achieving sustainability of all objectives requires gradual modification of forest ecosystems. Developing the recommended age class structures and patches for a landscape unit should be implemented gradually and adapted to local conditions. It may be difficult to achieve the recommended age class structure in landscapes with an extensive harvesting history, and it may take several rotations to meet the old age class structure objectives.

8. One must exercise caution when using FSOS. Improper weightings can result in unacceptable solutions such as the short-term depletion of old growth when meeting long-term patch targets (Figures 5.10 and 5.12).

There are numerous high quality solutions to the problems, and each solution has a different spatial pattern. From operations research perspectives, it is frustrating that there is no global "optimal" solution. However, from a forest management perspective, this is good news because it indicates robustness in the harvest schedule.

The thesis has made a unique contribution by developing and demonstrating a multiple objective model capable of handling large scale and long-term planning problems. The modeling approach is flexible and can be extended to problems where the consequences of conflicting objectives need to be evaluated.

Recommendations for future research

- More efficient algorithms should be researched to improve the speed (or allow for larger problems – i.e. entire Timber Supply Areas).
- Easier ways of identifying weightings and cooling rates should be identified.
- Efficient map overlay tools are needed to reduce the number of resultant polygons.
- An ability to schedule from multiple treatments is needed. Examples are alternative silvicultural systems and regeneration options.

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