APPLICATIONS OF SPATIALLY EXPLICIT TIMBER HARVEST SCHEDULING: SUSTAINED YIELD UNIT SIZE AND CORRIDOR ANALYSIS

by

KERRY BRIAN ROUCK

B.S.F., The University of British Columbia, 1994

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Department of Forest Resources Management

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

JULY 1995

© KERRY BRIAN ROUCK, 1995

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of FORESTRY.

The University of British Columbia
Vancouver, Canada

Date July 14, 1995

DE-6 (2/88)

ABSTRACT

This thesis addresses two major topics. First, impacts on timber supply and economics associated with sustained yield unit size are investigated. Partitioning the forest into sustained yield units is a complex task that involves assessing timber supply, allocation of cutting rights, and social, economic, and environmental impacts. There are numerous ways to vary the timing and intensity of harvests within individual drainages while still meeting the objectives of sustained yield. In this paper a spatial forest planning model is used to examine economic and environmental implications of varying the sustained yield unit size. Harvests for a Timber Supply Area in British Columbia are calculated using four sizes of sustained yield units: 1) 12 small units, 2) 4 moderately sized units 3) 2 large units, and 4) 1 unit representing the entire forest. Relative to the 12 small units, short-term (20 year) harvest levels for the Timber Supply Area increased by 7.6%, 10%, and 10.8% for the 4, 2, and 1 unit aggregations, respectively. Medium-(21-60 years) and long-term (61-120 years) increases in harvest levels averaged approximately 75% and 40%, respectively, of those realized in the short-term. Reductions in the length of active road and delivered wood costs were also observed as sustained yield units increased in size. Small units often restrict short-term timber supply and provide continuous road access to important wildlife habitat. While larger units afford greater flexibility in meeting short-term harvests, the intensity of the harvest within individual drainages increases. However, with large units the inactive drainages can be closed for extended periods, thus limiting human access to the active drainages.

Second, landscape level management strategies aimed at maintaining and enhancing biological diversity have given rise to the need to incorporate spatially explicit modeling techniques in timber supply planning. Of particular interest to forest managers is the requirement to maintain connectivity of critical habitats when developing harvest patterns. While identification of the habitat islands is a complicated issue, maintaining connectivity of the islands can be achieved through manual identification of stands, or by using algorithms which exploit the underlying network structure of spatially explicit forest inventory data. In this study, three methods of identifying corridors – permanent reserves, replacement corridors, and floating corridors – are compared with respect to the effects on harvested areas, timber supply, and road activity and corridor structure. Permanent and replacement corridors are identified manually, whereas floating corridors are located using a heuristic network algorithm. While permanent reserves are adequate for modeling short-term timber supply (< 20 years), the longevity of stands is questionable. Replacement corridors are intuitively attractive, but lead to substantial reductions in timber supply due to the additional reserved areas and long rotations. Timber supply impacts due to floating corridors vary according to the harvest constraints in place; heavily constrained areas respond similarly to permanent corridors, whereas loosely constrained areas benefit as stands become eligible for harvest late in the planning horizon.

Table of Contents

List of Tables

List of Figures

Acknowledgments

I would like to thank Dr. John Nelson for the inspiration, ideas, suggestions, endless hours of proof-reading, providing me with a computer and a place to work, and much-needed financial support. Couldn't have done it without you, John! Committee members Dr. Peter Marshall and Dr. Gordon Baskerville for taking an interest in my research. Professor Glen Young and Dr. Andrew Howard who both hired me as a teaching assistant over the past two years so that I didn't starve to death. Tim Shannon (World's Toughest Research Analyst), Dave Gizowski (programmer-extraordinaire), and whoever else is in the Forest Operations Research Group for the ATLAS model, algorithms and data preparation. I am also indebted to the Ministry of Forests in Revelstoke, F.E.R.I.C. and Timber West for providing the spatial data used in both these studies. Finally, I have to thank my wife, Lisa, for kicking me in the butt enough times so that I was able to complete this thesis on time.

Chapter 1

Introduction

1.1 Overview

This thesis uses spatial analysis to address two problems in forest level planning. The first study quantifies the impacts on timber supply and economics associated with varying the size of the constituent sustained yield units in a given timber supply area managed under complex, area-based harvest constraints. The second study uses the topological information inherent in spatially explicit forest inventory data to analyze the impacts on timber supply and road network activity associated with three modeling techniques used to include a system of corridors and linkages between critical habitat islands in a forest. In the remainder of this chapter, I give an overview of forest planning and timber supply models, followed by problem definitions for the two studies which comprise the bulk of this thesis.

1.2 Forest Level Planning

Forest level planning takes place at three non-distinct levels: strategic, tactical, and operational. Each level of planning is affected by the others. Basically, the strategic plan determines the goals of forest management, while the tactical and operational plans determine the spatial and temporal sequence of events used to achieve those goals. Both tactical and operational planning have received much research attention over the past decade (O'Hara *et al.*, 1989; Li, 1989; Sessions and Sessions, 1990; Nelson *et al.* 1995). While optimization techniques work well at the strategic level, gaming simulations and heuristics are practicable at the tactical and operational levels.

The traditional strata-based models used in the past are best suited for strategic planning purposes, but lack robustness and detail required for use at the tactical and operational level (Nelson *et al.*, 1993). Aspatial models are designed to recognize and track only the amount of area in a given state. This state is usually described by stand age, rotation age, growth characteristics, and silvicultural treatments. Aspatial data for large tracts of land are easily gathered and prepared, as detailed information about individual harvest units is not required. The area of all stands sharing like attributes is totaled, and harvests are extracted from this pooled area without regard to area-based rules such as adjacency constraints and greenup requirements. Harvested hectares are then assigned to a new state, depicting the amount of area in regenerated stands.

The need to incorporate non-timber resource values such as visual sensitivity and wildlife habitat objectives into the timber supply analysis has increased to the point that models must incorporate spatially explicit data. Furthermore, the aspatial strata-based models are neither capable nor designed to incorporate the data required to generate the finer resolution tactical and operational plans.

Forecasts of road construction and maintenance levels, adjacency constraints (harvest return interval for adjacent blocks) and greenup requirements require knowledge of topological relationship among harvest blocks, road networks, permanent reserves, and other features. Opening size restrictions are equally difficult to model using aspatial means. Furthermore, concerns have been raised that aspatial plans developed at the strategic level are not achievable at the tactical level. Although methods have been developed to estimate these constraints and guidelines in the aspatial models, accurate projections of timber supply at the tactical and operational level require that these constraints be explicitly defined (Nelson *et al.* 1993).

Spatially explicit timber supply and harvest scheduling models recognize and track the geographic location of individual harvest units over the entire planning horizon (O'Hara *et al.*, 1989). Attributes such as stand types, volume curves, and harvest systems can be assigned to each block. Additionally, information pertaining to the topology, or spatial arrangement of harvest units can be generated and used within the model. Harvest units are either pre-designed by forest engineers (Sessions and Sessions, 1990; Nelson *et al.* 1995), or are created by combining like-stands or raster cells within the model (Lockwood and Moore, 1993).

Spatially explicit models are generally quite flexible, and can be used to analyze many types of problems. In particular, these models can be used to exactly model adjacency constraints and greenup requirements, as each harvest unit and its neighbours are tracked individually. The inclusion of road networks in the model provides the means to forecast road construction and maintenance activity in addition to timber supply. Moreover, areas not targeted for timber extraction activity that contribute to non-timber resource values such as wildlife habitat or community watersheds can be included in the model.

Linking spatially explicit models to other models can offer additional information regarding management plans or policy that is otherwise not available from aspatial models. For example, the harvest schedule generated by a spatially explicit model can be used as an input for habitat assessment models. Similarly, hydrology models can use the resulting forest patterns to forecast water yields in community watersheds.

The major drawback with spatially explicit models is the time and effort required to prepare the required data. Although data can be extracted from a geographic information system (GIS), considerable time and expertise is needed to convert the data to a useful format. In addition, the design of pre-defined harvest units is a time-consuming task that requires detailed knowledge of the area of interest.

1.3 Sustained Yield Unit Size

Annual allowable cut calculations in British Columbia are made at the level of the timber supply area (TSA). There is, however, mounting pressure to manage considerably smaller land bases under a sustained yield policy (B.C. Ministry of Forests, 1991). This study addresses the issue of sustained yield unit size. More precisely, what are the effects on timber supply and economics associated with reducing the size of constituent sustained yield units managed under area-based harvesting guidelines? The problem arises from the notion that area-based harvesting constraints such as maximum allowable disturbance rates, and adjacency and greenup requirements become increasingly restrictive as the land base to which those constraints are applied is reduced. The goal of this study is to quantify the reductions in harvestable volume for a given area as the constituent units are decreased in size, and to provide an indication of the extent of changes in road network activity and delivered wood costs.

A spatially explicit harvest scheduling simulation model is used to develop 120-year harvest schedules for various sizes of sustained yield units comprising a timber supply area. Comparisons of the aggregated timber supply and other indicators for each size of sustained yield unit are then compared.

1.4 Analysis of Corridor Modeling Techniques

The mandate to maintain and enhance biological diversity has led to inclusion and consideration of landscape units when planning harvest patterns (B.C. Ministry of Forests, 1993a). Forest planners must recognize critical habitat areas in their development plans, and furthermore, ensure that these areas are connected by a corridor of mature forest stands. The challenge is to develop an algorithm which can be used to identify stands suitable for incorporation into the corridor while minimizing the impact on timber supply. Spatially explicit harvest scheduling models allow candidate stands to be identified and temporarily removed from the working forest land base, thereby permitting identification of one or more corridors. However, to minimize the impact on timber supply, and to allow for natural disturbances, it is desirable for the location of the corridors to be periodically redefined across the landscape (Sessions, 1992). Although previous work by Nelson and Shannon

(1994) addressed timber supply and delivered wood costs for permanent and replacement corridors, no studies have yet attempted to quantify the impacts and behaviour associated with the "floating" corridors proposed by Sessions (1992).

Three modeling techniques for incorporating corridors into the timber supply analysis are presented. Impacts on timber supply, road network activity due to the inclusion of corridors are quantified, and corridor dynamics are described.

1.5 Organization

This thesis proceeds as follows:

Chapter 2 describes the sustained yield unit size problem and quantifies the associated impacts on timber supply, road network activity, and delivered wood costs through the use of a spatially explicit harvest scheduling model.

Chapter 3 describes the connectivity issue as it relates to forest harvest pattern planning. Algorithms used to develop the networks are described and demonstrated, and applied to two case study areas.

Chapter 4 summarizes the solutions to the problems, and defines future research objectives.

Chapter 2

Sustained Yield Unit Size

2.1 Background

As public interest in British Columbia's forest resource reshapes traditional timber management practices, the current state of the forest inventory, as well as the methodology used to determine Annual Allowable Cut's (AAC's) has come under considerable public scrutiny. In 1976, the Pearse Commission of Inquiry into Forest Policy called for the aggregation of existing Public Sustained Yield Units (PSYU's) to create large Timber Supply Areas (TSA's) designed to serve major manufacturing centers (Pearse, 1976). As a result, AAC's are now determined on large TSA's throughout the province, some that exceed 2 million ha.. In the absence of area-specific harvest regulations, these large sustained yield units provide enormous flexibility for harvest scheduling. However, over the last decade, numerous watershed specific regulations (maximum disturbance rates for hydrology, retention of thermal cover for wildlife, etc.) have been introduced, and it is questionable whether large sustained yield units still offer such an advantage. Historically, cut-over watersheds and undisturbed watersheds were combined to produce uniform harvest flows, where the undisturbed watershed was harvested at a high rate until the cut-over watershed matured. Now, specific forest structures and landscape patterns must be maintained in every watershed, and opportunities to harvest one watershed at a high rate in order to offset age-class deficits elsewhere are limited.

The importance of managing forests for non-timber values such as water yields, recreational opportunities, wildlife habitat, and aesthetic values has changed the traditional forestry paradigms almost overnight. As a result, foresters must now attempt to ensure not only a sustainable supply of timber products, but must also demonstrate that ecosystem health is not compromised in the process. This is an enormous task, and it is forcing many practitioners towards detailed watershed level planning. To address the sustainability issue, these plans need to be spatially explicit and they must cover long time horizons. This planning process is ideal for managing individual watersheds on a sustained yield basis, but there are concerns that constraining harvest flows on individual units will negatively affect TSA harvest levels (B.C. Ministry of Forests, 1991). Similarly, managing each watershed within the TSA as a sustained yield unit may have negative environmental impacts because of increased accessibility to certain wildlife populations. Before the practice of managing each watershed in the landscape as an independent unit is adopted, the impacts of such widespread forestry activities on timber supply, wildlife populations, and other non-timber values need to be assessed.

The purposes of this study are to determine the effect of sustained yield unit size on timber supply and economics, and to examine the associated environmental implications. The Revelstoke Timber Supply Area is used as a case study. The TSA is partitioned into 12 compartments, which are first treated as sustained yield units, and subsequently aggregated to create larger sustained yield units. At each level of aggregation, a harvest schedule which maximizes short-term harvests is generated using a spatial forest planning model. Changes in timber supply, road network activity, and delivered wood costs are quantified at each level of aggregation. Possible ecological implications due to sustained yield unit size are also discussed.

This paper consists of five major sections. First, the forested land base of the Revelstoke TSA is described. Second, the harvest rules and assumptions used in the harvest scheduling simulation are described, along with a brief overview of the computer model. Third, a description of the process used to create the sustained yield units and the methods used to compare harvest levels are presented. Fourth, results are presented and analyzed. Finally, important issues related to sustained yield unit size are identified and discussed.

2.2 Study Area Description

The Revelstoke TSA is located in the rugged, south-eastern region of British Columbia. The TSA supports a wide range of recreational and tourism needs, it forms a strategic connection between two National Parks, and supports a local forest products industry. The main forest cover types include spruce (*Picea* spp.), balsam (*Abies lasiocarpa*), hemlock (*Tsuga heterophylla*) , western red cedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and western larch (*Larix spp.*).

Although the gross area of the TSA is in excess of 504,000 hectares, only 176,945 hectares of timber are considered to be of commercial quality[1]. Major deductions from the total land base can be broken down into the following categories: non-crown land (4% of total area), non-forest land (56%), and inoperable areas (22%) (B.C. Ministry of Forests, 1993). An additional 7% of the forested land base is reserved as environmentally sensitive areas, non-merchantable forest types, riparian areas, and avalanche chutes. Once other miscellaneous deductions are accounted for, the total land base available for harvesting is only 35% of the gross TSA area. Although all environmentally sensitive areas and inoperable blocks were designated "reserved" and are not eligible for harvest, they are included in the analysis because they contribute towards forest cover constraints. Figure 2-1 summarizes all commercial and reserved areas by age-class.

[1]This figure differs from that used by the B.C. Ministry of Forests (1993) in the Timber Supply Analysis of the Revelstoke TSA due to the difference in assumptions associated commercial forest types. For the remainder of this paper, the areas reported will be those used in our spatial analysis.

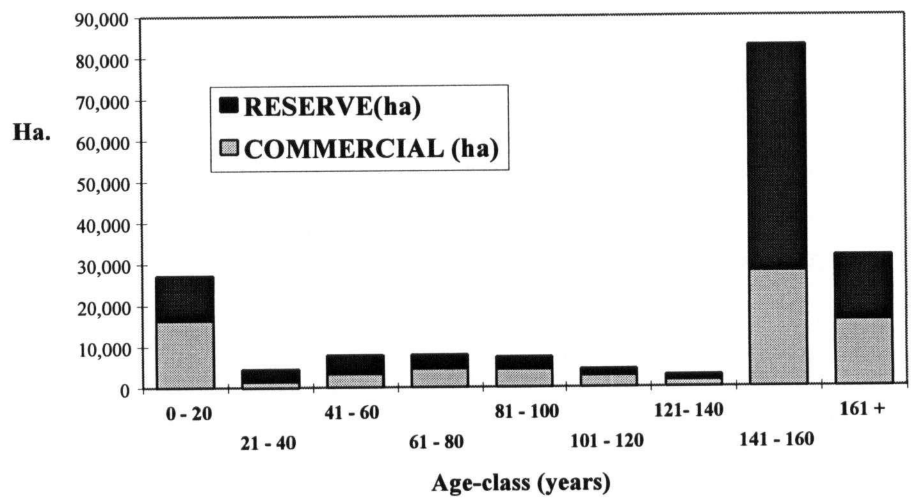

Figure 2-1. Summary of commercial and reserved areas in the Revelstoke TSA.

The data used in this study were compiled by the Revelstoke Forest District staff. Individual harvest units (or blocks) were located on 1:20,000 maps, and each block was assigned the following attributes: volume curve, silvicultural system, harvest system, initial age, and harvest zone. The data for the TSA included over 14,000 harvest units, slightly more than 18,000 road-links, 12 planning compartments, and 160 harvest zones.

2.3 Simulation Model

ATLAS is a computer simulation model used to examine short-term and long-term effects of spatial harvesting restrictions and silvicultural treatments using a block-by-block approach, rather than the traditional strata-based approach used by many other forest planning models (Nelson *et al.* 1995). As with other simulation models, the target harvest schedule must be found through iterative trials.

The largest geographic unit recognized by the model is the "planning compartment". Individual planning compartments can be subdivided into "zones" to which a unique harvesting rule can be applied. Rules like maximum disturbance rates and minimum forest cover requirements apply to individual zones. The smallest unit recognized by the model is the "harvest unit" (Figure 2-1). Within the model, unique combinations of attributes—block area, volume/age curves, initial stand-age, silvicultural systems, harvest systems, and road links—are defined and assigned to individual harvest units.

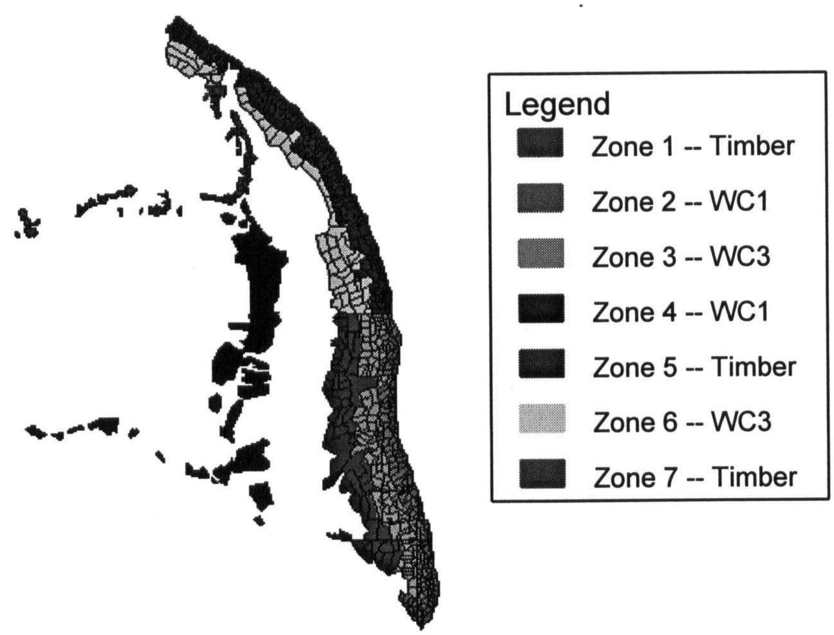

Figure 2-2. Planning compartment 5, showing zones and harvest unit boundaries. Each zone represents a geographic area to which a specific harvest rule applies.

2.3.1 Harvest Scheduling Algorithm

When simulating a timber harvest, ATLAS schedules harvest units according to a "closest block first" algorithm designed to minimize the amount of road constructed in each period. Harvest priorities are assigned to the planning compartments, then to each zone within the compartments, and finally, to each harvest unit within each zone. In this study, compartments at the southern end of the TSA have the highest priority, and those at the northern end have the lowest priority. Zone priority is based on the distance to the centre of the zone from a pre-determined major road link in the planning compartment. Likewise, the harvest priority rating of each harvest unit is based on its distance from the major road link in the planning compartment. In each planning period, the model selects blocks for harvest by first going to the highest ranked planning compartment, then to highest ranked zone within that planning compartment, and finally to the highest ranked harvest unit within that zone. Harvest units are selected in successive zones until either the target harvest is reached, or until constraints become binding. The entire forest is then aged one period, and the harvesting cycle is repeated. The simulation terminates when the planning horizon has been reached.

2.3.2 Harvest Rules

All simulations use a planning horizon of 120-years (approximately one rotation) and a planning period of 10-years. The harvest rules include adjacency and green-up, wildlife cover constraints, and visual quality restrictions. These rules are applied to the zones, which average 1,100 ha. in size. Table 2:1 summarizes the harvest rules and the amount of the TSA area affected by each.

2.3.3 Harvest Flow Constraints

Harvest levels were set to maximize short-term volume production, with a maximum 10% reduction per decade, until even-flow was reached. The decision to maximize short-term harvests is based partly on forest dynamics, and partly on current policy in the province. Changes in harvest levels associated with sustained yield unit size are largely, if not totally, a short-term phenomena. Over the long-term, in the presence of watershed level constraints, the forest reaches an equilibrium in age-classes and spatial patterns, and we would expect little or no gains to be realized by creating larger sustained yield units. However, in the short-term, age-class distributions and spatial patterns may be binding, and incremental gains in harvest levels may be realized by the additional scheduling flexibility offered by larger sustained yield units. By maximizing short-term volume production, we attempt to capture these incremental gains. Short-term volume maximization also helps to account for the fall-down effect which occurs as old-growth stands (high volume per ha.) are converted to managed stands (low volume per ha.). Further, there is considerable pressure from rural communities and the forest industry to keep AAC's at historical levels, and when it is determined that harvests must decline (either the falldown effect or non-timber values, or a combination of the two) these groups require a transition period, such as the 10% decline per decade, to adjust plant capacity and local economies.

Table 2:1. Harvest rules used in the Revelstoke TSA. The percentage of area to which each rule applies is shown on the right.

rule	description	green-up age (years)	maximum % of area under green-up	minimum mature cover age (years)	minimum % of area in mature cover	percent of TSA area
1	basic harvest rule	20	40	40	30	17
2	wildlife 1	20	40	80	60	12
3	wildlife 2	20	40	80	40	1
4	wildlife 3	20	40	80	52	50
5	visual 1	40	25	40	30	2
6	visual 1 & wildlife 3	40	25	80	52	2
7	visual 2	40	10	40	30	1
8	visual 2 & wildlife 1	40	10	80	60	5
9	visual 2 & wildlife 2	40	10	80	40	2
10	visual 2 & wildlife 3	40	10	80	52	7
11	no harvest	n/a	n/a	n/a	n/a	1
Total						**100%**

2.4 Sustained Yield Units

The TSA was first subdivided into 12 planning compartments, averaging 14,745 ha. (Figure 2-3a). Each compartment contains approximately 3 watersheds averaging around 5,000 ha.. We chose not to model individual watersheds as sustained yield units for two reasons. First, the large number of watersheds in the TSA (at least 36) make this an onerous and impractical task, and second, clusters of about 3 watersheds typically have distinct geographic boundaries and form logical planning cells for administration purposes. Each of the 12 planning compartments was treated as a sustained yield unit during the harvest simulations. The harvest schedules from each unit were then summed to determine the total harvest for the TSA. This is referred to as the BASE case.

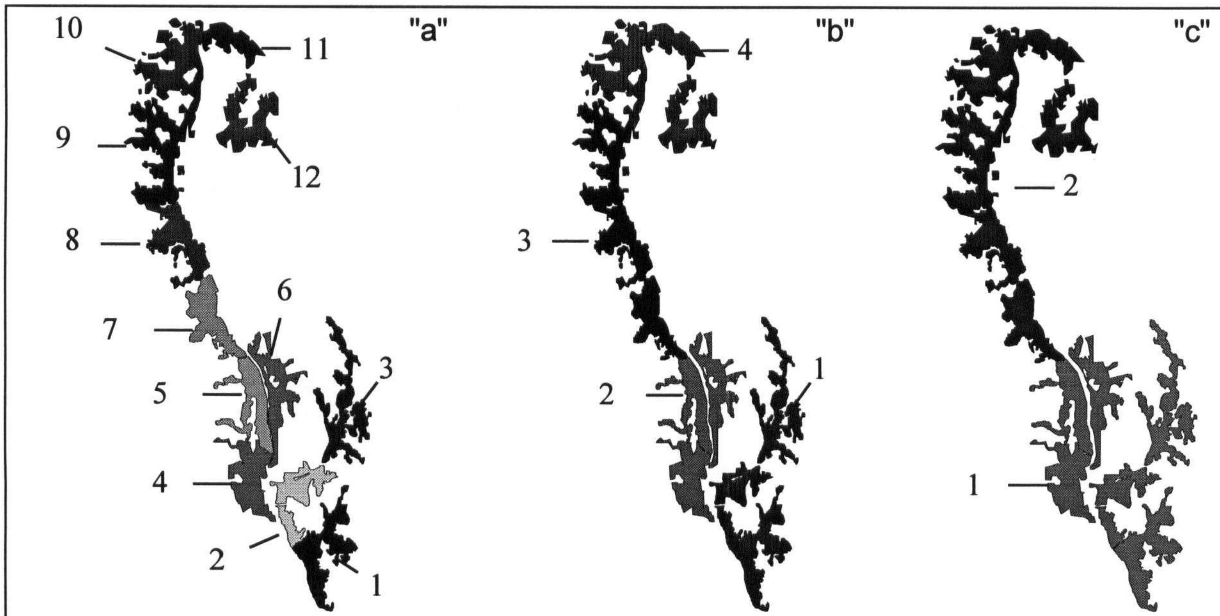

Figure 2-3. Forested area of the Revelstoke Timber Supply Area showing a) the 12 planning compartments, b) the 4 sustained yield units from the first level aggregation, and c) the 2 sustained yields units from the second level aggregation. The third level aggregation, (not shown) includes all 12 planning compartments.

The next phase, referred to as the first level aggregation (FLA), involved combining 3 contiguous planning compartments to form 4 larger sustained yield units (Figure 2-3b). For example, sustained yield unit 1 consists of planning compartments 1-3. The average size of the sustained yield units in the FLA is 44,250 ha.. For each of these sustained yield units, harvest schedules were generated using the same periodic harvest flow constraints used in the BASE case. Periodic harvests from each of the FLA sustained yield units were then summed to find the harvest schedule for the TSA.

For the second level aggregation (SLA), 2 sustained yield units were constructed from 6 contiguous planning compartments (Figure 2-3c). For example, SLA-1 consists of planning compartments 1-6. Each of these larger sustained yield units represents approximately one-half of the TSA, and averages 88,750 ha.. Again, 120-year declining-flow harvest schedules were generated for each sustained yield unit, and the results were summed to the TSA level.

Finally, for the third level aggregation (TLA), all 12 planning compartments were combined into a single sustained yield unit, representing the entire TSA (176,944 ha.). As with the other simulations, the TLA sustained yield unit was harvested using the 120-year declining-flow harvests specified in the previous aggregations. Figure 2-4 shows the steps involved in the aggregation process, and the area of each sustained yield unit.

Once a feasible harvest schedule had been generated for each sustained yield unit, the ATLAS model was used to generate a series of reports describing the harvests and related economic indicators. Periodic values were produced for the following indicators: 1) harvest area, 2) harvest volume, 3) delivered wood costs, and 4) length of active roads. In addition, the short- (0-20 years), medium- (21-60 years), and long-term (61-120 years) averages for selected indicators were calculated at each level of aggregation.

Delivered wood costs are reported in $\$/m^3$, and are the sum of the logging, road construction, road maintenance, and hauling costs. When the delivered wood costs were calculated for aggregated compartments, a volume-weighted average was used.

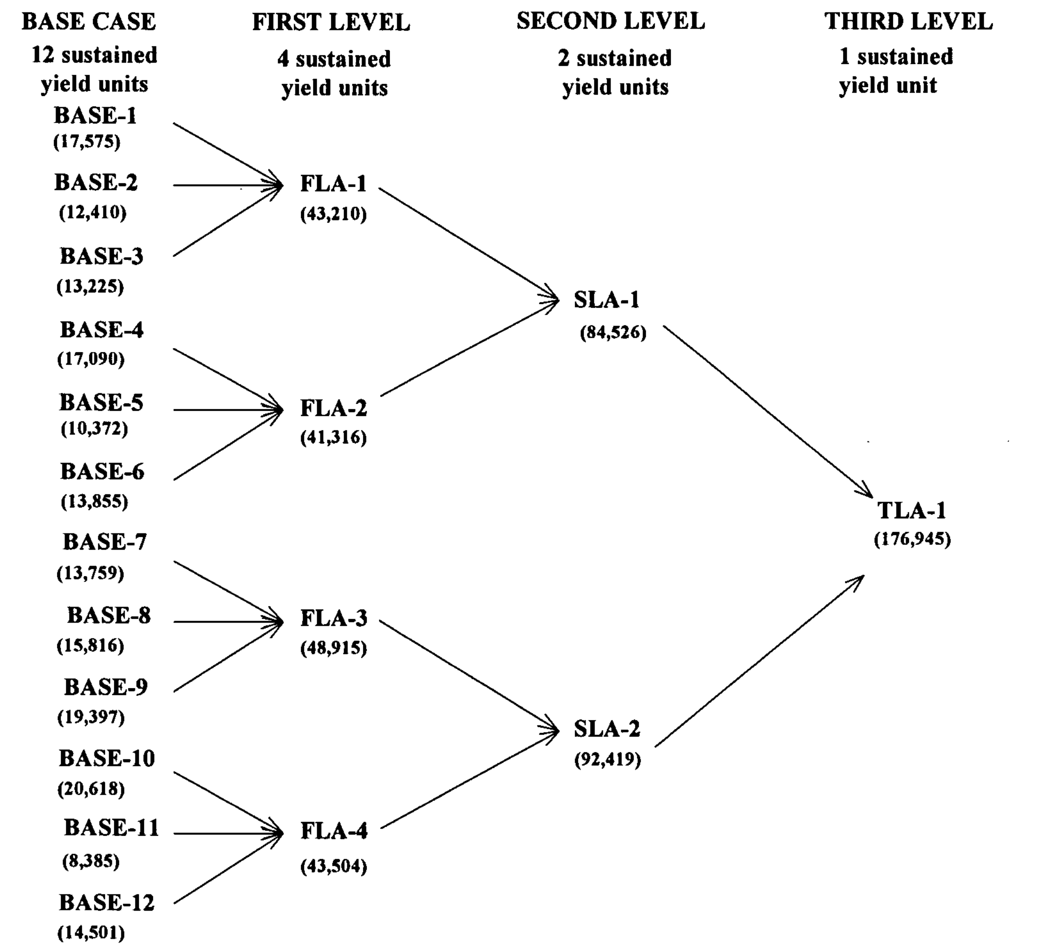

Figure 2-4. Steps in the aggregation process used to create the sustained yield units. The numbers in brackets are the total forested area of each sustained yield unit.

2.5 Results And Discussion

Overall, the results demonstrate expected trends as sustained yield units increase in size. In general, the area and volume harvested increase as sustained yield unit sizes increase, while delivered wood costs decrease and active road lengths decrease. Between successive levels of aggregation, the trends for area and volume are strong, while the trends for delivered wood costs and active road lengths are not so well-defined. Each of these indicators are analyzed below.

2.5.1 Harvest Area

Summary statistics for harvest areas and volumes resulting from the aggregation process are presented in Figure 2-5 and Table 2:2.

As shown in Figure 2-5, the area harvested increases as the size of the sustained yield units increases. The larger units afford more options when adjacency constraints and green-up requirements lead to gridlock problems. The short-term increase in harvested area translates directly to an increase in harvested volume, particularly for the SLA and TLA aggregations, where the harvested area increases by 10.0% or more. Increases persist throughout both the medium- and the long-term for all levels of aggregation, indicating that benefits can be realized far into the future. This is most likely due to the difficulty in breaking free from the rigid landscape pattern established by the adjacency rule. This pattern tends to repeat itself in subsequent harvests, and it can be very difficult to alter. Wallin *et al.*, (1994) refer to this as "land-use legacies in forestry".

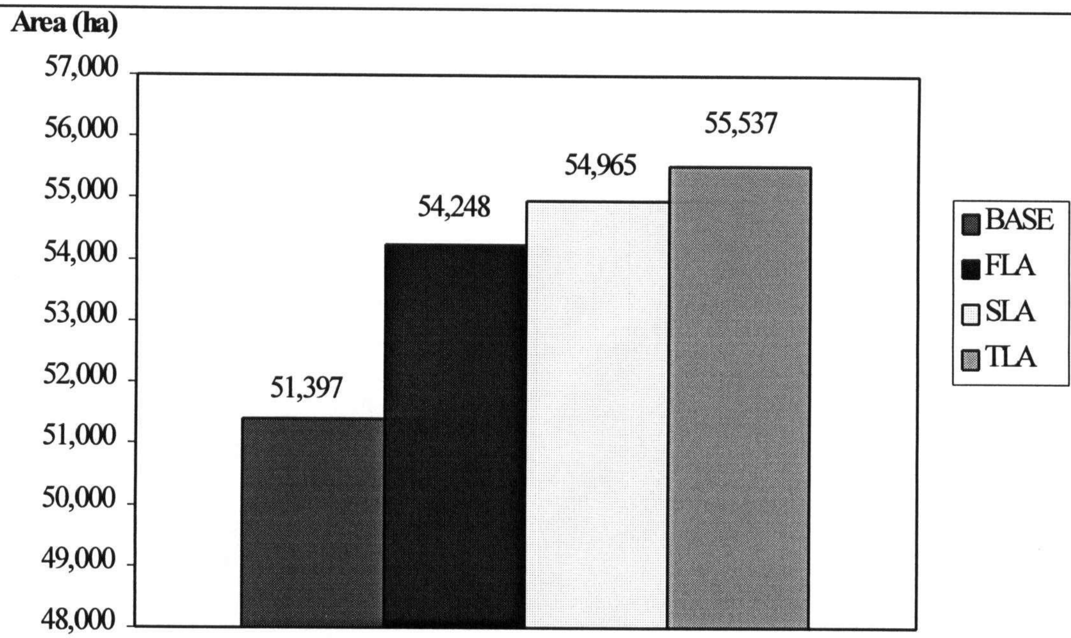

Figure 2-5. Total area harvested by sustained yield unit size. Total area harvested increases with sustained yield unit size.

Table 2:2. Percent change in the area harvested for all levels of aggregation, relative to the BASE case. The mean represents the sum of all sustained yield units, and the range shows the extremes observed in individual units.

Unit	Number of Units	0-20 years mean (range)	21-60 years mean (range)	61-120 years mean (range)
FLA	4	**7.4** (5.7 - 13.9)	**5.4** (4.2 - 6.4)	**4.6** (-1.0 - 7.7)
SLA	2	**10.0** (9.4 - 10.3)	**7.6** (5.3 - 9.3)	**4.5** (-3.9 - 11.9)
TLA	1	**11.2**	**9.1**	**6.2**

2.5.2 Harvested Volume

Summary statistics for the effects on harvest volumes resulting from the aggregation process are presented in Figure 2-5 and Table 2:3.

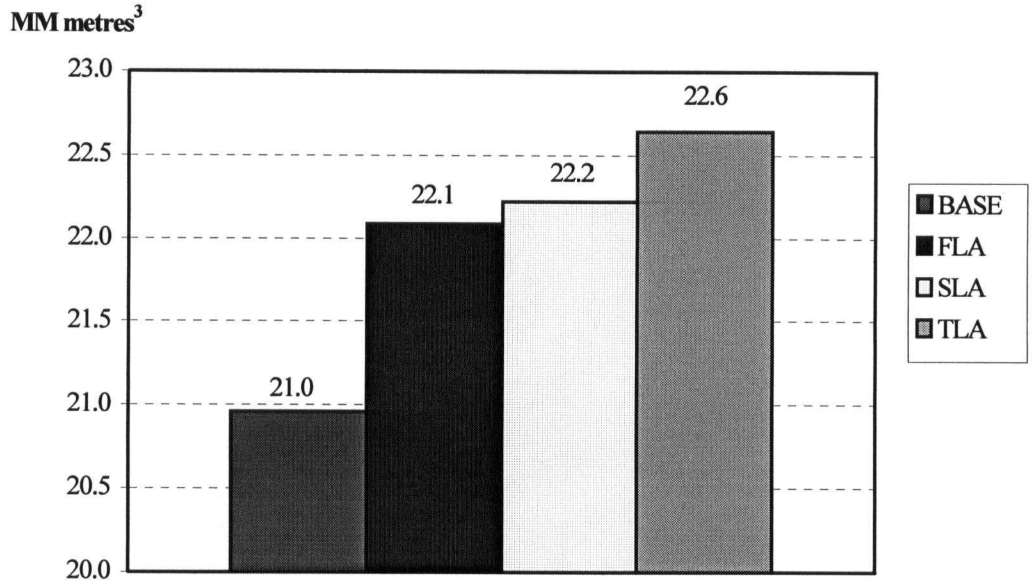

Figure 2-6. Total harvest volume by sustained yield unit size. Maximum harvest is achieved with the TLA, while the summation of the 4 FLA units or the 2 SLA units generate slightly lower total harvests. A significant decrease in harvest volume occurs when the 12 BASE compartments are treated as independent sustained yield units.

Table 2:3. Percent change in harvest volumes for all levels of aggregation, relative to the BASE case. The mean represents the sum of all sustained yield units, and the range shows the extremes observed in individual units.

Unit	Number of Units	0-20 years mean (range)	21-60 years mean (range)	61-120 years mean (range)
FLA	4	**7.6** (5.3 - 12.5)	**5.4** (4.1 - 7.3)	**3.9** (-0.3 - 6.5)
SLA	2	**10.0** (9.1 - 10.7)	**7.7** (4.4 - 10.2)	**2.1** (-3.7 - 7.1)
TLA	1	**10.8**	**8.8**	**5.5**

2.5.2.1 First Level Aggregation

When compared to the sum of the BASE case, the FLA's showed a substantial increase in harvest volume. Overall harvest volumes increased from 21.0 MM m^3 to 22.1 MM m^3 (Figure 2-6). Of the four FLA units created, short-term harvest volumes increased the most in FLA-1 (12.5%). The reason for this sizable increase can be attributed to the initial age-class profiles in the constituent planning compartments (1-3), as well as the high proportion of zones designated as visual and wildlife areas. When these BASE compartments were aggregated, the number of possible harvest locations increased, and gridlock problems caused by adjacency constraints and green-up requirements were alleviated. Increases remain positive throughout the remainder of the planning horizon, with medium- and long-term increases of 5.4% and 3.9% respectively.

2.5.2.2 Second Level Aggregation

Increases in harvest volume for the second level aggregation surpassed those for the first level by only 135,000 m^3, yet when compared to the sum of the BASE planning compartments, the SLA yielded substantial increases in harvest volumes. Total harvest volumes increased from 21.0 MM m^3 to 22.2 MM m^3 (Figure 2-6). Short-term harvest volumes were similar for both the SLA compartments, however, medium- and long-term average increases were highest in SLA-2 (10.2%). This difference can be attributed to the initial age-class profiles in the two compartments—the south half of the TSA (SLA-1) having a longer history of harvesting than the northern half (SLA-2). In addition, the high proportion of zones having a combination of visual and wildlife resource emphases in the southern half results in the deferral of mature blocks which must be retained to satisfy these landscape constraints. Substantial increases in harvest volumes persist throughout the remainder of the planning horizon (medium-term = 7.7%, and long-term = 2.1%), but decrease in magnitude as second rotation stands are harvested in the later periods. Interestingly, long-term timber supply in SLA-1 is lower than when BASE compartments 1-6 are treated as independent units (a reduction of 3.7% results from the aggregation).

These long-term reductions in SLA-1 are likely caused by the high harvest rates in the short-term, relative to the BASE case. Relative to SLA-1, the low, short-term harvest rates in the BASE case allows some stands to be postponed until the latter periods. The combination of beginning inventory and harvest constraints in the SLA-1 aggregation results in an increase in short-term harvests, partly at the expense of long-term harvests.

2.5.2.3 Third Level Aggregation

The largest increase in harvest volume was obtained in the third level aggregation (TLA). Relative to the BASE case, harvest volumes increased from 21.0 MM m^3, to 22.6 MM m^3 (Figure 2-6). Short-, medium-, and long-term harvest volumes increased by 10.8%, 8.8%, and 5.5%, respectively. The substantial increase in the long-term average may be a result of having achieved the harvest target during the early periods in planning compartment 1-8, thereby making planning compartments 9-12 available during the later periods. In the third level aggregation, when the entire TSA is treated as the planning compartment, maximum scheduling flexibility is available, both in the short and long-term.

2.5.3 Delivered Wood Costs

Summary statistics for delivered wood costs ($/$m^3$) related to the aggregation process are presented in Figure 2-7 and Table 2:4.

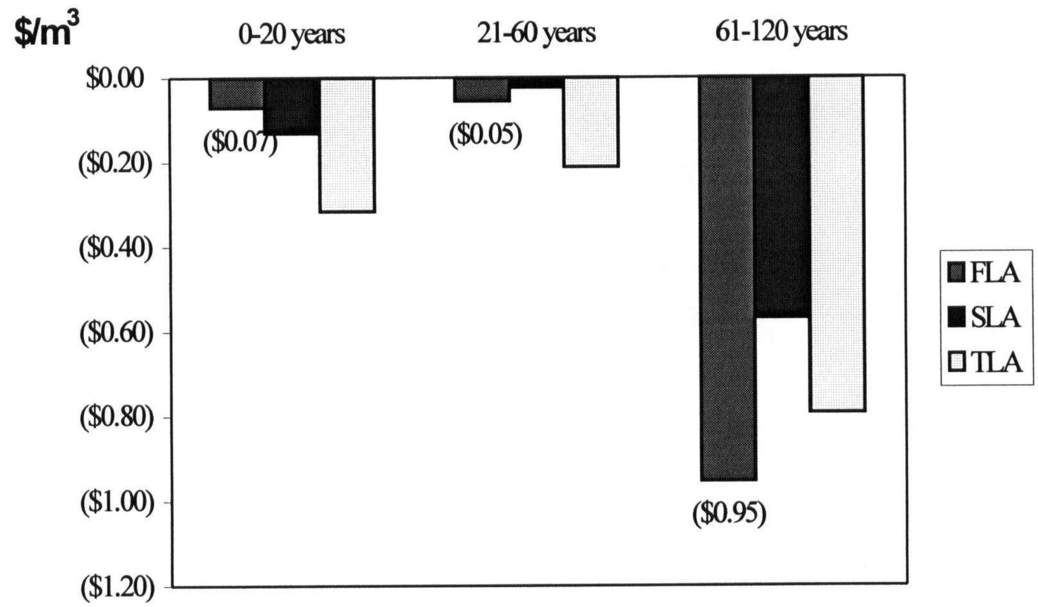

Figure 2-7. Change in delivered wood costs relative to the BASE case, for the short-, medium-, and long-term.

Table 2:4. Changes in delivered wood costs ($\$/m^3$) for all levels of aggregation, relative to the BASE case. The mean represents the sum of all sustained yield units, and the range shows the extremes observed in individual units.

Unit	Number of Units	0-20 years mean (range)	21-60 years mean (range)	61-120 years mean (range)
FLA	4	**-0.07** (-.68 - 0.80)	**-0.05** (-0.54 - 0.44)	**-0.95** (-1.61 - -0.62)
SLA	2	**-0.13** (-0.14 - -0.13)	**-0.02** (-0.44 - -0.27)	**-0.57** (-0.63 - -0.59)
TLA	1	**-0.32**	**-0.21**	**-0.79**

Delivered wood costs (DWC) are not as clearly affected by sustained yield unit size as are the area and volume harvested. Short-term results indicate a slight reduction in DWC with increasing sustained yield unit size (Table 2:4). Medium-term results are fairly consistent, showing the most economically-sized unit to be the TLA, with a reduction of $\$0.21/m^3$. However, over the long-term, the FLA compartments have the lowest cost-permetre ($0.95/$m^3$ reduction relative to the BASE case). These differences are mostly due to construction and maintenance of the road network.

Up to period 7, periodic changes in the delivered wood costs (relative to the BASE case) fluctuate between positive and negative for all levels of aggregation. This fluctuation is attributed to the adjacency constraints and the associated effect on the construction of the road network. In the initial period, the existing road network is exploited leading to low DWC. In the second period, adjacency constraints result in high levels of road construction as new areas are accessed. Harvesting in the third period exploits this recent construction, while the fourth period sees harvesting dispersed once again, along with increased road construction and maintenance costs. This cycle continues until the road network is fully constructed (approximately period 8), at which time the changes in DWC remain negative. The overall decrease in DWC resulting from aggregation is due to fewer active roads (less road maintenance costs) than in the BASE case where every planning compartment is active during every period.

2.5.4 Active Roads

Summary statistics for the length of active roads for all aggregation levels are shown in Figure 2-8 and Table 2:5.

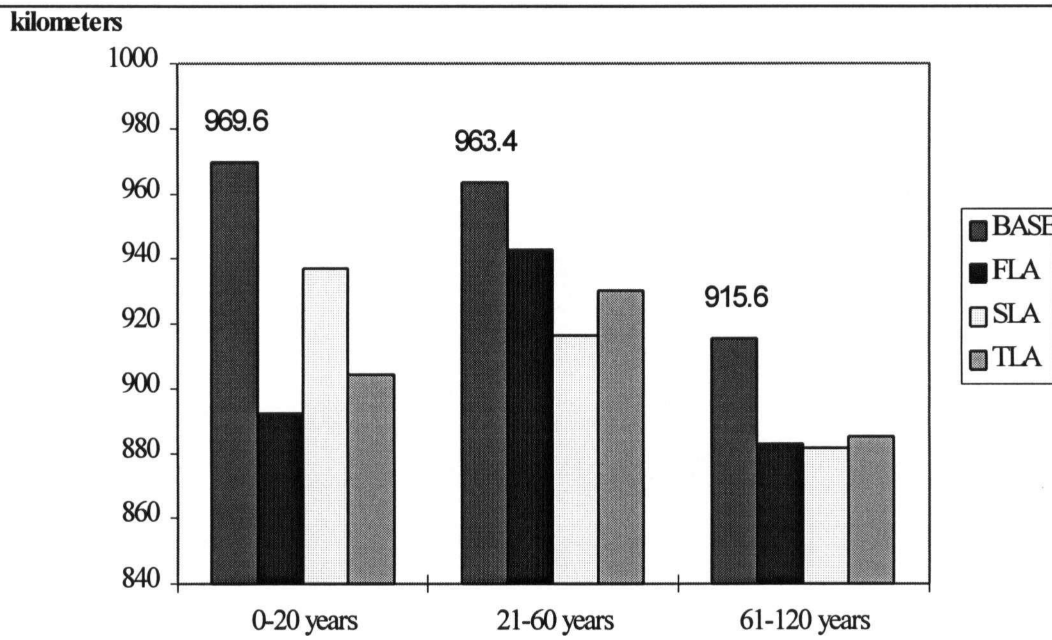

Figure 2-8. Short-, medium-, and long-term average lengths of active roads for all levels of aggregation. The BASE case results in substantially more active roads than does any other size of sustained yield unit. The relatively high short-term value for the SLA can be attributed to an abundance of immature timber in the southern part of the TSA.

Table 2:5. Percent change in length of active roads for all levels of aggregation, relative to the BASE case. The mean represents the sum of all sustained yield units, and the range shows the extremes observed in individual units.

Unit	Number of Units	0-20 years mean (range)	21-60 years mean (range)	61-120 years mean (range)
FLA	4	**-7.7** (-20.3 - -3.8)	**-2.0** (-11.6 - -1.1)	**-3.8** (-8.4 - -1.5)
SLA	2	**-3.1** (-5.7 - -3.2)	**-4.9** (-5.7 - -5.6)	**-3.9** (-1.3 - -9.5)
TLA	1	**-6.5**	**-3.1**	**-3.2**

Although active roads decrease substantially in the short-term, relative to the BASE case, the trend does not indicate a strong relationship to sustained yield unit size (Figure 2-8). The short-term decrease in the average length of active roads can be mainly attributed to having achieved the target harvest levels in the first two periods without accessing all the planning compartments. Medium- and long-term trends, however, do show a recognizable trend towards having fewer kilometers of active roads in the larger sustained yield units. The inconsistency in the short-term is likely due to historical harvesting patterns and the transition from a historical three-pass harvesting system, to the four pass system dictated by the adjacency rules used in the simulations. Upon adoption of a four pass system, existing road networks must be rapidly expanded to satisfy the adjacency constraints. More consistent trends emerge once the entire road network has been established, and the transition period has passed.

2.6 Discussion

Some generalizations can be made from the results. First, it appears that the maximum total harvested volume is realized when the TSA is managed for declining-flow harvests over its entirety. Second, the size of the sustained yield units can be decreased from the current size (176,945 ha. TSA) by a factor of 4 to the size of the sustained yield units represented by the first level aggregation (44,250 ha.) without significant adverse impacts on volume flows, and without increasing the amount of active roads over the entire TSA. However, decreasing the size of the planning compartments beyond those in the FLA can result in significant negative impacts to short-term timber supply, and increase the amount of active roads on the landscape. Third, the increase in timber supply as a result of increasing the sustained yield unit size appears to persist throughout the planning horizon, a phenomena related to the inflexible landscape pattern created by adjacency constraints. Finally, a reduction in delivered wood costs and the abundance of active roads appears to have some relation to sustained yield unit size, but tends more to be sensitive to the spontaneous expansion of the road network resulting from the introduction of adjacency constraints.

Despite the low variation in total wood supply over the long-term, it is inevitable that over the short-term, some compartments will suffer immediate timber shortages. The severity of this shortage will of course depend on the current age-class structure of each unit and the harvest rules (Davis and Johnson, 1987). This is was found to be the case in our study—in particular, BASE compartments 2 and 7 have a history of high harvest rates, and hence, the short-term timber availability in these units is low. Furthermore, the conversion from the historical three-pass harvesting system, to the four-pass system often results in an effective "gridlock" in the harvest schedule.

Obviously, the flexibility in harvest scheduling patterns afforded by the larger sustained yield units can help offset short-term timber deficits, and avoid the occurrence of gridlock conditions due to adjacency rules. If one is prepared to relax the adjacency rules to relieve gridlock problems, the spatial model is very useful in identifying the conflicting harvest units.

Smaller sustained yield units will likely affect non-timber resources. Active roads and roaded areas, for example, are likely to be much more abundant across the landscape due to continuous harvesting in each small sustained yield unit. In this study, we reported the changes in active roads for the entire TSA. Although the total length of active roads decreased with increasing sustained yield unit size, periodic changes within certain watersheds were much more pronounced.

This temporal variation can be demonstrated by plotting the harvest activity in individual planning compartments when managed at two different levels of aggregation. For example, Figure 2-9 shows the periodic harvest levels for BASE compartments 1 and 10 when each is managed as an independent unit (BASE-1 and BASE-10), and when they both are included within the aggregated sustained yield unit for the entire TSA (TLA). Recall that compartment 1 is located in the southern region of the TSA and has the highest harvest priority. Compartment 10, located in the northern region has a low harvest priority. It can be seen that compartment 1 is subject to constant harvesting activity over the 120-year planning horizon, regardless of the size of the sustained yield unit. However, the intensity of harvest varies significantly when it is managed as part of the aggregated unit, TLA. When compartment 10 is managed as part of the entire TSA, periods of high harvest intensity are followed by long intervals with little or no activity. This pattern contrasts strongly with the continuous harvest flow when compartment 10 is managed as an independent unit. Which harvest flow pattern is preferable from a non-timber perspective is not clear. It can be argued that moderate, continuous harvests have low impacts on ecosystem health, or it can be argued that periods of heavy timber extraction, followed by long intervals of inactivity constitute a better practice (Hunter, 1990). By specifying a minimum harvest level in each planning compartment, the TLA harvest levels shown in Figure 2-9 could be altered to extend the return intervals. Minimum harvest levels were not specified in our study.

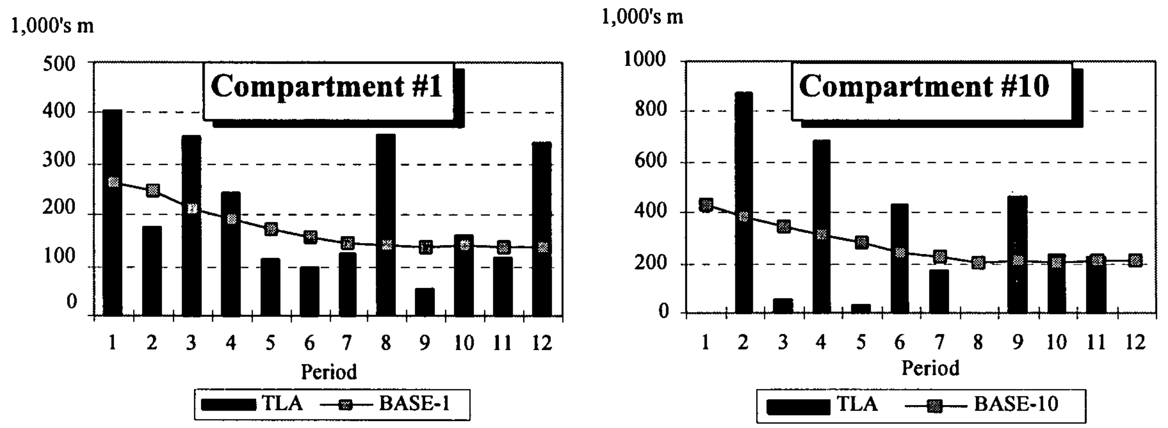

Figure 2-9. Comparison of harvest levels in compartments 1 and 10 when scheduled as individual units (BASE) and as part of the entire TSA (TLA). Each schedule satisfies watershed level constraints, however, differences in intensity of harvest, and the length of the return interval are apparent.

Most large ungulates, like moose and elk avoid areas with a high concentration of active logging roads (Rost and Bailey, 1979; Ward, 1975). For example, moose favour a heterogeneous mosaic of young and mature stand-types containing an abundance of early seral stands (Eastman, 1978). These conditions would exist in the smaller planning compartments where harvesting is continuous, but essentially all the habitat has road access. Woodland caribou, which prefer upslope habitats and reside in areas supporting an abundance of arboreal lichens, are highly migratory creatures and require suitable habitat over a large land base. These requirements could be satisfied by managing large sustained yield units which allow harvests to be dispersed over a long periods of time, and over a large land base. Combining long return intervals with appropriate road deactivation in individual watersheds, may provide better quality habitat and reduce harassment by humans (Stevenson and Hatler, 1985).

While there may be preferences to restricted access for wildlife, there are economic and forest management concerns that favour a more accessible forest. Long return intervals and limited access with the presence of insects and disease increases the risk of catastrophic outbreaks. Pests endemic to the Revelstoke TSA (spruce bark beetles and the hemlock looper) have caused substantial losses in the TSA over the past decade (B.C. Ministry of Forests, 1986; 1993). Wind-throw, fire, and root rot are other natural forces that create the need for salvage operations and accessibility throughout the TSA.

At the outset, we described the trend towards watershed level planning, and possible movement towards defining sustained yield units at this level. In this study we did not model watersheds as sustained yield units because of the major work load this would entail. In the Revelstoke TSA this could easily tally up to 36 units, creating an impractical workload for forest administrators. Defining even smaller sustained yield units will increase the number of harvest flow constraints across the TSA, and lead to even greater volume reductions than observed for the 12 planning compartments. Over the long-term, smaller sustained yield units also imply an even greater level of continuous human activity throughout every watershed in the forest.

In some cases, local communities and industry have strong reasons for postponing immediate AAC reductions, and the short-term harvests are maintained at historical levels and subsequently allowed to decline at rates greater than 10% per decade. In these circumstances, the flexibility offered by large sustained yield units would prove to be highly advantageous for meeting the immediate timber supply needs. If we had modeled these harvest flow constraints in our simulations, we expect that the increases in short-term harvest levels associated with the larger units would have been greater.

Finally, the harvest rules, the initial age-class structure, and existing landscape patterns will strongly influence the results. More rigid rules, especially those controlling maximum disturbance rates and green-up ages, will tend to negate incremental gains related to larger units. When watersheds with deficits in the older age-classes and unfavourable landscape patterns are incorporated into large sustained yield units, significant incremental gains in short-term harvest levels will be realized.

2.7 Conclusion

Determining the ideal size of sustained yield units is a complex problem. Key factors are the harvest rules, harvest flow constraints, initial conditions of the forest, plus the timber and non-timber values desired. Specific to timber values in the Revelstoke TSA, this study found that the TSA could be partitioned into four sustained yield units (averaging 44,250 ha.) without causing serious reductions in timber supply or significant increases in delivered wood costs. Further aggregation to larger units produced only minor gains in harvest levels. Relative to the smallest sustained yield units, the larger units offer greater harvest scheduling flexibility, opportunities to concentrate harvesting operations in specific watersheds, and less administration in terms of determining AAC's. However, smaller management units may offer greater flexibility for salvaging damaged timber, and they appear to be environmentally friendly to the public eye.

The effects of unit size on non-timber resources must also be given consideration, but here we have much to learn. With small units, non-timber resources may either be compromised, or benefit as sustainable harvests are implemented in watersheds throughout the forest. The impact of widely distributed, low intensity harvests (and active logging roads) on wildlife populations is a case in point. Further research in this area is critically needed. Another confounding problem is whether recreational opportunities will increase due to improved access, or decline because of the widely dispersed timber on the landscape. The effects of increased road construction and logging activity on water quality and fisheries values are also important factors to consider in the decision.

We have grown accustomed to the harvest scheduling flexibility afforded by an abundance of mature timber and large sustained yield units. Meanwhile, protection of non-timber resources and the transition to managed stands has placed downward pressures on AAC's. A multitude of regulations now control forest structure and landscape patterns in individual watersheds, and while these limit harvest scheduling flexibility, there are still gains, especially in the short-term, from scheduling harvests with large sustained yield units. This can help alleviate short-term timber supply problems, and with careful access management, it may be possible to minimize human impacts on wildlife.

Chapter 3

Corridor Analysis

3.1 Background

Of the many issues facing forest land managers today, none is quite so ominous as the potential loss of biological diversity in natural systems. Biological diversity is defined as "the variety and abundance of species, their genetic composition, and the communities, ecosystems, and landscapes in which they occur" (SAF, 1991). The topic of biological diversity has been studied intensively over the last two decades on a continuum of geographic scales, from the regional level (> 1 million hectares) (Prance, 1990), to the stand level (< 100 hectares) (Schoonmaker and McKee, 1988). As the demand for wood products continues to increase, it is important that we recognize that the capacity of the forest to continue to deliver these goods depends on our ability to maintain and enhance biological diversity. While human activities affect biological diversity at all levels, perhaps the most visible and direct effects are due to forest management activities (Burton et al, 1992).

One of the most challenging mandates foresters must address at this time is that of maintaining connectivity within landscapes. Connectivity refers to the presence or absences of travel corridors and interconnections between habitat islands (Harris, 1984). The concept arose from studies of tropical ecosystems in the Brazilian rainforest and has since been extended to the Pacific Northwest with the intent of providing a series of connectors between parks and other forest reserves. Connectivity is also a keystone element in the emerging concept of "ecosystem management" and the associated effort to minimize habitat fragmentation and isolation (Brooks and Grant, 1992).

If we accept that connectivity is an important issue in terms of landscape-level management, then timber supply models must somehow recognize and incorporate the necessary features for maintaining the connectivity of habitats within a landscape. Otherwise, timber supply projections will be over-estimated for any given land base. The problem can be viewed as having two components: 1) identification of habitat islands, and 2) identification of the connecting corridors between these islands.

The identification of habitat islands is a lengthy and difficult task that requires extensive field studies and life history knowledge of the species of interest, and thus, is beyond the scope of this study. Once these areas have been identified, however, they are easy to include in any timber supply model. The habitat islands are simply removed from the working forest land base, and become ineligible for harvest activities.

Stands intended to serve in a connector may or may not be eligible for harvest. At present, three methods are used to design and include corridors in long-term forest planning models. The simplest method entails identifying suitable areas for use as connectors, and permanently reserving these areas from the working forest land base.

Although this method may be practical for developing short-term (<20 years) harvesting plans, it lacks robustness in areas with frequent natural disturbances because of the low probability that these stands will remain intact for long periods of time. A second method uses primary and secondary (replacement) corridors designed to alternately serve as connectors. This method requires additional area to be set aside for the secondary connector, and that the stands in the connector be harvested at an extended rotation age. A third method of incorporating corridors into the long-term planning process was developed by Sessions (1992). He uses the underlying network structure of spatially explicit forest data to identify linkages between two habitat islands, which allows the corridor to "float" over the landscape through time according to stand dynamics and management intervention. Although impacts on harvest volumes and economics have been addressed for the fixed and replacement methods by Nelson and Shannon (1994), the behaviour and impacts on harvest volumes associated with Sessions' algorithm have yet to be quantified. By allowing corridors to move across the landscape through time, the net effect should be to increase the amount of commercial forest area that is available for harvest, resulting in a corresponding increase in harvest volume relative to the permanent and replacement methods.

The objectives of this study are: 1) to investigate the behaviour of each of the three corridor modeling techniques (fixed, replacement, and "floating" corridors) by quantifying impacts on timber supply projections, and 2) to describe the dynamics of the floating corridors in response to three different objective functions.

This paper will be presented in the following order. First, a description of corridors and linkages as they pertain to forest management is presented. The second part of the paper focuses on the description of the algorithms used to design single and multiple linkages between special habitat areas. Next, case studies testing the algorithms are presented for Hardwicke Island and the Nehaliston Creek Watershed. Fourth, comparisons of timber supply, corridor characteristics, and road network activity for each of the three modeling techniques are presented for a 150-year planning horizon. Finally, conclusions and recommendations for further research are made.

3.2 Corridors and Forest Ecosystem Networks

On June 15, 1995 the British Columbia government introduced the Forest Practices Code (FPC) — a document designed to regulate timber harvesting throughout the province. The FPC contains an abundance of rules, regulations and field guides designed to minimize detrimental effects of timber harvesting on wildlife, water, and visual resources. Of particular interest is the requirement that harvest patterns maintain a certain degree of connectivity across a landscape. In particular

> "...harvest patterns and cutblock designs must, wherever possible:
>
> - incorporate a network of mature-sized timber distributed throughout the landscape, sufficiently linked to maintain wildlife travel and dispersal corridors, riparian habitat, and social and recreational values. A proportion of the mature-sized timber patches must be large enough to protect plants and animals that require such forested habitats to survive."
>
> (B.C. Ministry of Forests, 1993a, p. 57)

Recently, the term "Forest Ecosystem Network", or FEN, has been adopted to refer to the habitat islands and the system of linkages and interconnections between them. In B.C., FENs are to be designed at the landscape unit level. Landscape units generally consist of one watershed, or a series of similar watersheds, and range from 5,000 to 50,000 hectares in size (B.C. Ministry of Forests, 1992). Among other things, FENs are designed in part to minimize the impacts of forest fragmentation, provide some level of forest interior habitat or refuge areas, provide a continuum of relatively undisturbed habitat for indigenous species, and serve as travel corridors for other species (B.C. Ministry of Forests, 1995). It is important to remember that the FEN is only one component of a landscape level design, and that the surrounding forest matrix is just as important to the survival of species (Franklin, 1993). Obviously, the corridor of mature and old-growth timber is only one component of the FEN, however, removing these high-volume stands from the working forest land base can cause a substantial reduction in the volume available for harvest from a given landscape unit. This study focuses on how harvest scheduling simulations can incorporate corridors into the FENs, and thereby provide more accurate projections of timber supply.

3.3 Methodology

The methods outlined here exploit the network structure which underlies forest planning problems (Sherali and Liu, 1990). In order to understand the nature of the network structure, and to fully develop the methodology used in identifying the location of the floating corridors, I will first define the general terminology used in network analysis. Then, the general shortest path problem is presented, followed by a description and worked example of a heuristic solution to a minimum Steiner tree problem. Finally, the modifications made to the algorithms to address the corridor problem, and the harvest scheduling model used for the timber supply projections are described.

3.3.1 General Network Terminology

For the purposes of this paper, only a few select terms are needed. In general, a network consists of a set of "nodes" connected by "arcs". Nodes can be thought of as locations, such as junctions or towns on a road map. In this study nodes refer to polygons, or individual harvest units. Arcs simply connect adjacent nodes. In the road map example, arcs would be analogous to roads, and would connect nodes, or junctions. In the forest planning problem, arcs are more of a concept than a physical reality. By knowing the nodes (harvest units) that each arc starts and ends at, and the length of the arc, a description of the topology, or spatial arrangement of the harvest blocks in the forest can be generated. A more conceptual use of arcs is to use them represent the "cost" of moving between nodes. In the case of the road map, the arcs may represent the cost per kilometer of driving from town A to town B, rather than the distance between the two points. Similarly, in the forest planning problem, the arc connecting two polygons can represent the cost of the road required to access the second polygon from the first, or in the case of corridors, the cost of extending a corridor comprised of the two adjacent polygons.

3.3.2 The Shortest Path Problem

The shortest path algorithm is used to determine the optimal sequence of arcs which connect two nodes of a network in such a way that the distance (or cost) is a minimum. The distance between nodes can be physical distance, or some form of a cost associated with traveling from one node to another. Formally, Bertsekas (1991) defines the shortest path between two nodes as being the path with "minimum length (cost) over all paths with the same origin and destination nodes". Although an extensive amount of work has been done on shortest path algorithms (Deo and Pang, 1984), only a few algorithms are used widely (Bertsekas, 1991). In the context of designing corridors in forest ecosystem networks, a shortest path algorithm can be used to define the set of polygons that can be temporarily deferred from harvest to provide a suitable corridor between two permanently reserved areas or habitat islands.

3.3.2.1 Dijkstra's Labeling Algorithm

One of the fastest and most practical shortest path algorithms was developed by Dijkstra (1959), and is commonly referred to as "Dijkstra's Labeling Algorithm". Briefly, the algorithm begins by assigning to each node a label which represents the cost of reaching that node from the source node (*s*). The labels are flagged as temporary and are assigned a high initial value. The source node (*s*) is set as the current node (*c*) and adjacent nodes labels are updated to indicate the distance (cost) of reaching them based on the value of the connecting arcs. When the sum of the costs of the sequence of arcs cost leading to a given node is less than that of its temporary label, the value is reduced to reflect this new cost. The values assigned to all temporary labels are then compared, and the node with the minimum label is flagged as "permanent", and set as the current node (*c*).

This labeling process is repeated until the label on the destination node (*t*) has been set to permanent, at which time the cost of the shortest path from the source node (*s*) to the destination node (*t*) has been identified. The set of nodes used in the path can then found by starting at the destination node, and working backwards through the series of permanent labels and adjacent nodes until the origin is reached.

Formally, Dijkstra's labeling algorithm can be described in four steps, as presented by Smith (1982):

Step 1 Assign a temporary label $l(i) = \infty$ to all nodes $i \neq s$; set $l(s) = 0$, set $c = s$. Make $l(s)$ permanent. (c is the last node to be given a permanent label).

Step 2 For each node i with a temporary label, redefine $l(i)$ to be the smaller of $l(i)$ and $l(c) + d(c,i)$. Find the node i with the smallest temporary label, set c equal to this i, and make the label $l(c)$ permanent.

Step 3 If node t has a temporary label, then repeat step 1. Otherwise, t has a permanent label, and this corresponds to the length of the shortest path from s to t through the network.

Step 4 For each permanently labeled node j other than s of the network, define $r(j) = i$ where $l(j) = l(i) + d(i,j)$ and $i \neq j$. Stop.

One of the few drawbacks of Dijkstra's algorithm is that only arcs having zero or positive lengths can be handled by the algorithm. In order for negative arc lengths to be incorporated, however, a nontrivial transformation of lengths must be performed in order to make all arcs a non-negative value (Bazaara and Langley, 1974). Conversely, other shortest path algorithms such as Ford's and Floyd's algorithms are capable of dealing with negative arcs, but they require a substantially greater computational effort (Smith, 1982).

3.3.2.2 A Sample Problem

To demonstrate the application of this algorithm, I have adapted an example from Smith (1982). The application of the algorithm to solve the shortest path problem for Figure 3-1 follows.

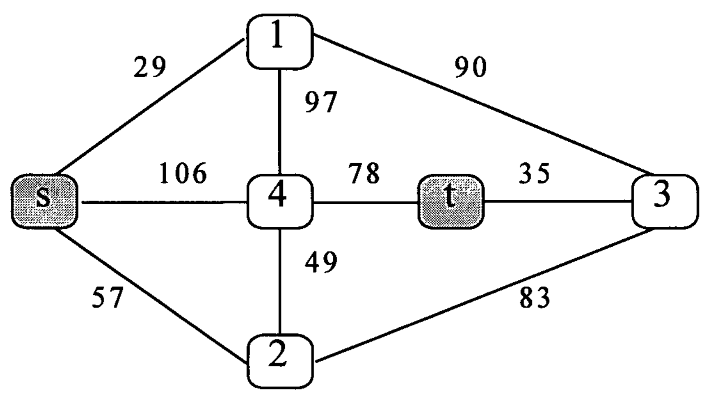

Figure 3-1. Sample network used to demonstrate Dijkstra's Labeling Algorithm (adapted from Smith, 1982). Distances associated with each arc are shown between nodes.

Iteration 1

Step 1 indicates that a permanent label be attached to each node and that the start node label be flagged as permanent.

	s	1	2	3	4	t
Label ( )	0	∞	∞	∞	∞	∞
Permanent?	yes	no	no	no	no	no
Current Node	c					

Step 2 redefines the labels to be the smaller of $l(i)$ and $l(c) = l(c) + d(c,i)$; changes the flag on the temporary label with the minimum value to permanent; and sets $c = 1$.

$l(i) = \min(l(i), l(c) + d(c,i)) = ?$

$c = s,\ i = 1$ $\quad l(1) = \min(\infty, 0 + 29) = 29$
$c = s,\ i = 2$ $\quad l(2) = \min(\infty, 0 + 57) = 57$
$c = s,\ i = 3$ $\quad l(3) = \min(\infty, 0 + \infty) = \infty$
$c = s,\ i = 4$ $\quad l(4) = \min(\infty, 0 + 106) = 106$
$c = s,\ i = t$ $\quad l(t) = \min(\infty, 0 + \infty) = \infty$

The set of labels now becomes:

	s	**1**	**2**	**3**	**4**	**t**
Label ( )	0	29	57	∞	106	∞
Permanent?	yes	yes	no	no	no	no
Current Node		**c**				

Step 3 stipulates that *Step 2* is repeated until c = t.

Iteration 2

Step 2 redefines the labels; sets c = 2

	s	**1**	**2**	**3**	**4**	**t**
Label ( )	0	29	57	119	106	∞
Permanent?	yes	yes	yes	no	no	no
Current Node			**c**			

Step 3 stipulates that *Step 2* is repeated until c = t.

Iteration 3

Step 2 redefines the labels; sets c = 4

	s	1	2	3	4	t
Label ( )	0	29	57	119	106	∞
Permanent?	yes	yes	yes	no	yes	no
Current Node					c	

Step 3 stipulates that *Step 2* is repeated until c = t.

Iteration 4

Step 2 redefines the labels; sets c = 3.

	s	1	2	3	4	t
Label ( )	0	29	57	119	106	184
Permanent?	yes	yes	yes	yes	yes	no
Current Node				c		

Step 3 stipulates that *Step 2* is repeated until c = t.

Iteration 5

Step 2 redefines the labels; sets c = t

	s	1	2	3	4	t
Label ( )	0	29	57	119	106	154
Permanent?	yes	yes	yes	yes	yes	yes
Current Node						c

Step 3 stipulates that when $c = t$, the value of the shortest path from s to t has been found.

Step 4 identifies the path from s to t by defining $r(j) = i$ where $l(j) = l(i) + d(i,j)$ and $i \neq j$.

j	$l(j)$	i	$l(i)$	$d(i,j)$	$l(i) + d(i,j)$	**In Path?**
1	29	s	0	29	29	**Yes**
2	57	s	0	~~57~~	57	No
3	119	1	29	90	119	**Yes**
4	106	1 (or 2)	29 (or 57)	97 (~~or 49~~)	126 (or 146)	No
t	154	3	119	35	154	**Yes**

For this example, working backwards from row "t", the shortest path from s to t passes through the nodes $\{s, 1, 3, t\}$ and has a value (cost) of 154 units (Figure 3-2).

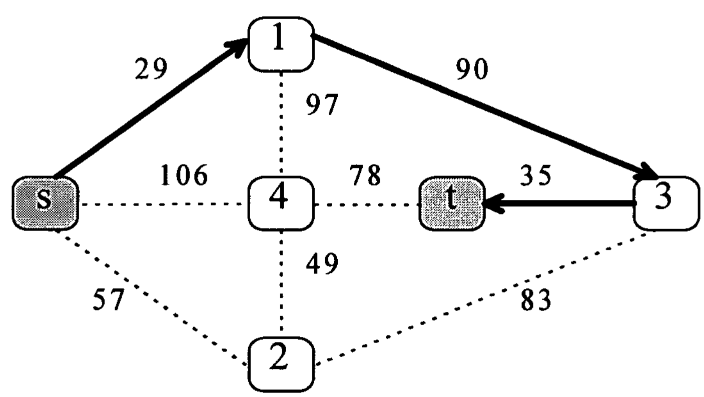

Figure 3-2. Shortest path solution generated using Dijkstra's Labeling Algorithm (adapted from Smith, 1982).

3.3.3 The Minimum Steiner Tree Problem

Among the extensions of the classical shortest path problem is the minimum spanning tree problem. In this problem *all* nodes in the network are joined by at least one connecting arc in such a manner that the sum of the costs of all the included arcs is a minimum. A considerably more complex extension of this problem is to define a subset of nodes to be connected by a minimum spanning tree. This type of problem is known as a minimum Steiner tree problem, named for the Swiss geometer Jacob Steiner. If we accept that the arrangement of harvest blocks in a forest has an underlying network structure, then we can envision a FEN as being a subgraph of the overall network. The habitat islands are analogous to the subset of nodes, and must be connected by a corridor, or a spanning tree. In particular, if we attempt to design the corridors in such a way that the reduction in the working forest land base is minimized, then we can view this design problem as having the properties of a minimum Steiner tree (Sessions, 1992).

The search for a fast and efficient algorithm to solve the minimum Steiner tree problem has been intense; however, an efficient algorithm has yet to be put forward. Several algorithms solve the problem; however, all are computationally intensive, and require considerable amounts of computer time (Hwang and Richards, 1992). To date, fast algorithms have been developed to address only the special cases (*e.g.*, Salowe and Warme, 1995). Most exact algorithms which address the graphical case require $O(k^n)$ operations (where k is some number, and n is the number of nodes in the network), resulting in solution times that increase exponentially as the number of nodes in the network increases. It is believed that no polynomial ($O(n^k)$) solution exists (Winter, 1987), and therefore, heuristic algorithms which are capable of closely approximating the optimal solution should be used in practice.

3.3.3.1 Sessions' Heuristic Solution to the graphic Steiner Network

Sessions (1992) proposes a heuristic algorithm which generates an approximate solution to the graphic Steiner network. The basic algorithm is described as follows:

Step 1 Identify the subset of nodes to be connected. Call this subset the set of "critical nodes".

Step 2 Randomly select one of the critical nodes and designate it the "destination node"

Step 3 Randomly designate one of the remaining critical nodes as the "source node", and solve the shortest path problem for these two nodes.

Step 4 Set all the arcs in the path identified in Step 3 to have a value of zero

Step 5 Repeat Step 3 until all critical nodes have been incorporated.

This method often generates a sub-optimal solution to the problem, but has very fast solution times, making it practicable for forest planning and harvest scheduling analyses. Furthermore, multiple solutions can be easily generated by varying the order in which the critical nodes are selected from the queue.

3.3.3.2 A Sample Problem

To demonstrate this problem, I have designed a simple graph consisting of 8 nodes and 12 arcs, each with a positive length.

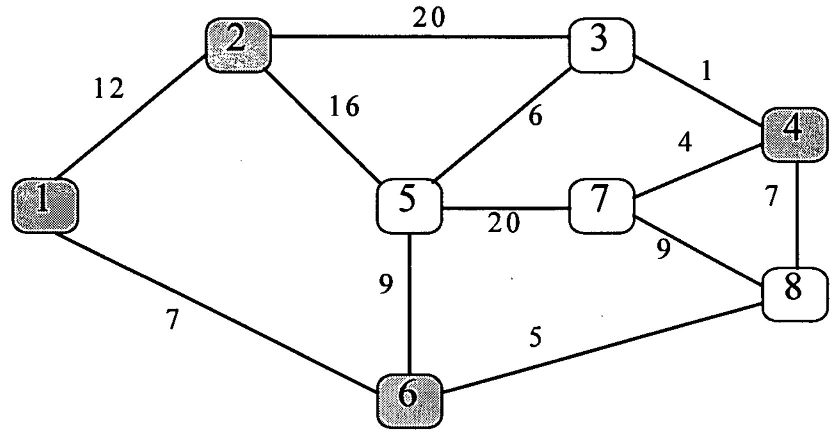

Figure 3-3. A sample network used to demonstrate Sessions' (1992) heuristic solution to the Steiner network problem. Numbers between nodes represent the cost of traveling along that arc.

In this example, nodes N2, N4, N6, and N1 are arbitrarily selected to be the critical nodes, node N2 is designated to be the destination node, and N4 is used as the first source node. Solving the shortest path from N4 to N2 gives the sequence (N4, N3, N2) with a cost of 21 units. Next, the cost assigned to arcs (N3, N4) and (N2, N3) are set to zero. The next source node is N6, and the shortest path to N2 is (N6, N8, N4, N3, N2), with a cost of 12 units. Finally, setting arcs (N6, N8) and (N4, N8) to zero cost, and selecting N1 as the source node gives a shortest path to N2 described by the sequence (N1, N6, N8, N4, N3, N2) with a cost of 7 units. The overall spanning tree has an total cost of 40 units, and is shown in Figure 3-4.

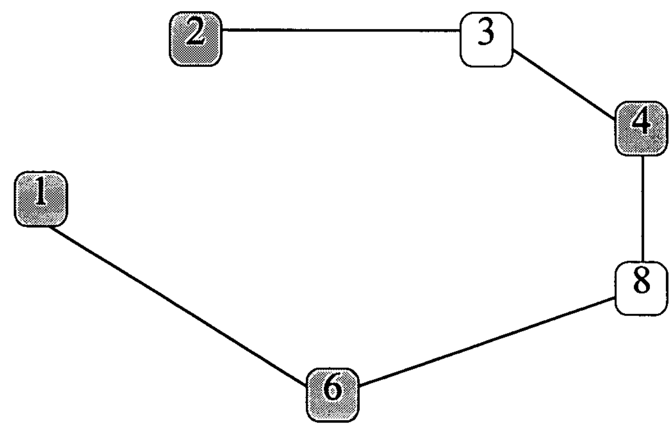

Figure 3-4. A possible spanning tree due to Sessions' (1992) heuristic solution to the minimum Steiner tree problem.

It is important to note, however, that the order in which the source nodes are selected from the list can affect the sequence of the final spanning tree. For instance, choosing node N1 as the destination node, rather than N2, and selecting the source nodes in the order N2, N4, N6, results in a final spanning tree with a value of only 31 units, consisting of the arcs connecting nodes (N2, N1, N6, N8, and N4). Sessions (1992) suggests that this discrepancy can be overcome by adopting a Monte Carlo approach for node selection, or to solve all possible sequences of node selections, then to choose the minimum solution. However, the additional time required to solve all possible combinations may outweigh the benefits of using this heuristic, especially when the number of nodes in the subset of critical nodes is large. For example, for a FEN having 4 critical nodes (habitat islands), the number of permutations, and hence solutions, would be 4! = 24. A FEN with 10 habitat islands, however, would require 10! = 3.63 million solutions! If we assume that a reasonably efficient computer program of Dijkstra's labeling algorithm can solve 10 shortest paths per second, this many solutions would require on the order of 4 days to solve – clearly not a practical alternative.

3.3.4 Further Modifications

In an attempt to speed up the algorithm proposed by Sessions (1992), and to closer approximate an optimal solution to the minimum Steiner tree, further modifications specifically designed for locating corridors in FENs at the landscape unit level have were developed.

3.3.4.1 Distance Ranking of Habitat Islands

The floating corridor algorithm must be linked to a spatially explicit harvest scheduling model. Hence, exploitation of the spatial timber inventory data required for the harvest scheduling model is possible. An "inter-island distance matrix" was developed using the geographic location of the user-identified habitat islands. The linear distances between islands are calculated and stored in a matrix, which is then sorted into an ascending list of pairs of habitat islands based on the inter-island distance.

This modification addresses the specific nature of the FEN problem in two ways. First, by selecting critical blocks in close proximity to each other, the FEN expands from the regions of high habitat island density to those areas where fewer habitat islands are present. Second, because stands separating habitat islands are typically comprised of large areas of relatively similar age-classes, many nodes need to be examined. Thus, selecting critical blocks based on geographic location reduces the number of nodes that need to be analyzed in each step of the shortest path algorithm, and therefore, decreases solution time.

3.3.4.2 General Modifications

Rather than use Sessions' (1992) simple non-directed graph to represent the network of harvest units in the forest, I chose to use a directed graph to represent the polygon network. For a non-directed graph (Figure 3-3), the cost of moving from node A to node B is the same as moving from node B to node A. However, for a directed network, the cost of moving between two nodes may be different, depending on the direction of movement. In the directed network generated for this study, each polygon is assigned a non-dimensioned "cost of inclusion" which represents the "cost" to the FEN of incorporating that harvest block in the corridor. The cost of the arc entering a polygon is based solely on the age of the polygon being entered, and not its adjacent neighbours. Conversely, Sessions' uses one-half the sum of the costs of blocks currently being analyzed to generate the cost of each arc, thereby reducing computer memory requirements, and increasing computational efficiency.

The difference between the directed and non-directed graphs in terms of polygon selection and the resulting network is negligible; however, the directed network may be more efficient when complex methods of cost determination are used. For example, if the common edge length of adjacent stands were to be used in the calculation of arc values, a directed network would be more efficient in storing these values, as the cost of entering a polygon would then depend on which side it is being entered from.

Finally, the length of the edge common to two adjacent polygons is calculated. Only polygons having a common edge greater than a user-specified minimum are incorporated into the network. This reduces the probability of a "narrow" polygon being incorporated into the corridor. Due to the non-uniform shape of the pre-defined harvest units, the chance of having a narrow section of corridor exists. This problem could be overcome by considering the "perimeter to area" ratio, or the length of the common edge between polygons when generating the cost of inclusion for each polygon.

3.3.5 Linking to a Spatially Explicit Harvest Scheduling Model

The harvest scheduling model has the capacity to perform harvest simulations either with, or without floating corridors. If a floating corridor is desired, a cost of inclusion in the corridor is assigned to each eligible polygon, based on its age at the time of harvest. User-defined habitat island polygons are read from data files and sorted based on the "inter-island distance matrix" described above. The first pair of habitat islands in the list are linked by a shortest-path algorithm and the cost-of-inclusion for all polygons in the sub-corridor is then reduced to zero. The next pair of habitat islands are then chosen, and the process is repeated until all habitat island pairs in the list have been connected. The polygons comprising the resulting corridor are reserved from harvesting for the current period.

The harvest scheduling simulation model used in this study is a deterministic simulation model which is run independently from the corridor model. Pre-defined harvest units (blocks) are queued according to a "closest-block first" harvesting priority. In each period, candidate polygons are selected from the queue. Stand- and landscape-level constraints applicable to that particular block are evaluated, and the block is either harvested, or left to grow. This process is repeated for each polygon until the target harvest level for the given period is achieved, or all polygons in the queue have been processed. Once a suitable harvest level has been found (through iteration), the appropriate road-links are activated to generate the road network required to service the polygons treated in a given period.

3.4 Case Studies

The floating corridor algorithm was applied on two forests: the Nehaliston Creek Watershed, located in the north Thompson River drainage; and Hardwicke Island, located in Johnstone Strait. For each forest, projections of timber supply are made with three corridor models – fixed, replacement, and floating. These projections are compared to a base case in which no FENs are present. To determine how the floating corridors respond according to the prescribed costs, three cost curves were used to analyze the floating corridor case. Harvest volumes and age-class distributions for each case are reported and compared to the BASE case.

3.4.1 Site Description

3.4.1.1 Hardwicke Island

The majority of the Hardwicke Island consists of second growth timber, with a few scattered patches of old-growth (Figure 3-5).

Table 3:1. Summary of harvest rules and the area to which each applies for Hardwicke Island. Hectares affected by each rule are categorized as commercial and reserved.

Rule	**Greenup Period (years)**	**Max. Age for Early Seral Stage (years)**	**Max. % of Zone Area in Early Seral Stage**	**Minimum Mature Age (years)**	**Min. % of Zone Area in Mature Seral Stage**	**Hectares Affected**	
						Commercial	Reserved
Timber	9	19	30	40	20	**3,734**	**83**
Visual 1	19	19	5	40	20	**2,180**	**96**
Visual 2	19	19	15	40	20	**1,038**	**115**
					TOTAL	**6,952**	**294**

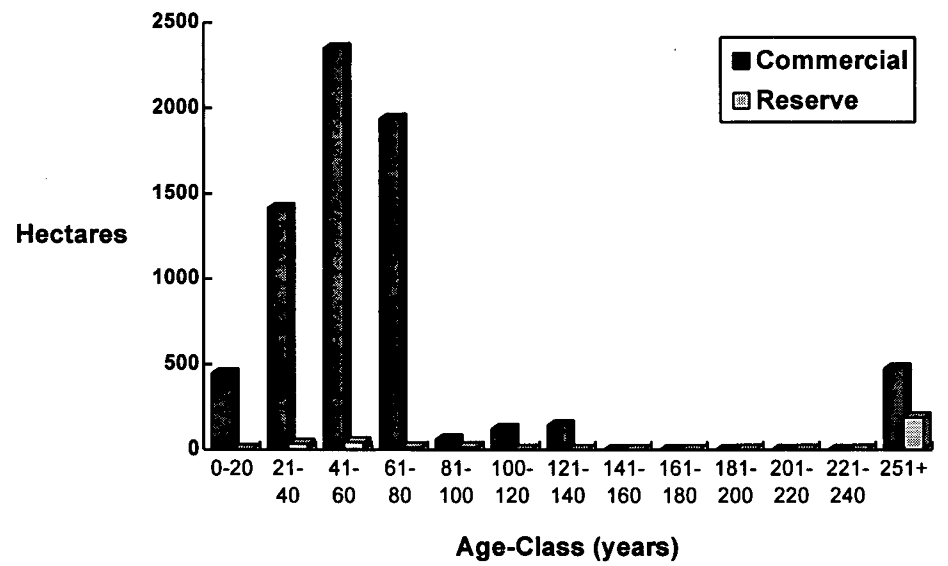

Figure 3-5. Initial age-class distribution for Hardwicke Island forest. "Commercial" stands are eligible for harvest, whereas "Reserve" stands are not.

A total of eleven "zones" were identified for the island – each having a major resource emphasis, and a corresponding set of harvest constraints such as seral stage requirements and green-up ages specifying the time between the harvesting of adjacent stands. The rules and the area to which the are applied are summarized in Table 3:1. A total of five site-classes are recognized, with minimum rotation ages of 1) 60-years, 2) 60-years, 3) 70-years, 4) 80-years, and 5) 160-years.

Hardwicke Island data were supplied by Timber West of Nanaimo and prepared by the Forest Operations Research Group at UBC. The 453 polygons which comprise the data set, average 16 hectares in size – ranging from 1 to 61 hectares.

3.4.1.2 Nehaliston Creek Watershed

The Nehaliston Creek Watershed is located in the North Thompson river drainage basin in the interior of British Columbia. The major feature of the area is the abundance of lakes and swamps which, when combined, comprise approximately 10% of the area of the watershed. The majority of the stands in the forest are in the 100- to 140-years-old age classes (Figure 3-6).

Only a single resource emphasis zone was used in this study, depicting a major resource emphasis geared towards timber production. Hence, a single rule is applied to the entire forest. A description of this rule and the area summary for the watershed are presented in Table 3:2.

A total of eleven stand types are recognized, based on a combination of the biogeoclimatic subzone and leading species on the site. Each stand-type has a corresponding volume-over-age curve. The minimum rotation ages are 90-years for Lodgepole Pine, and 120-years for Douglas-fir and Engelmann Spruce.

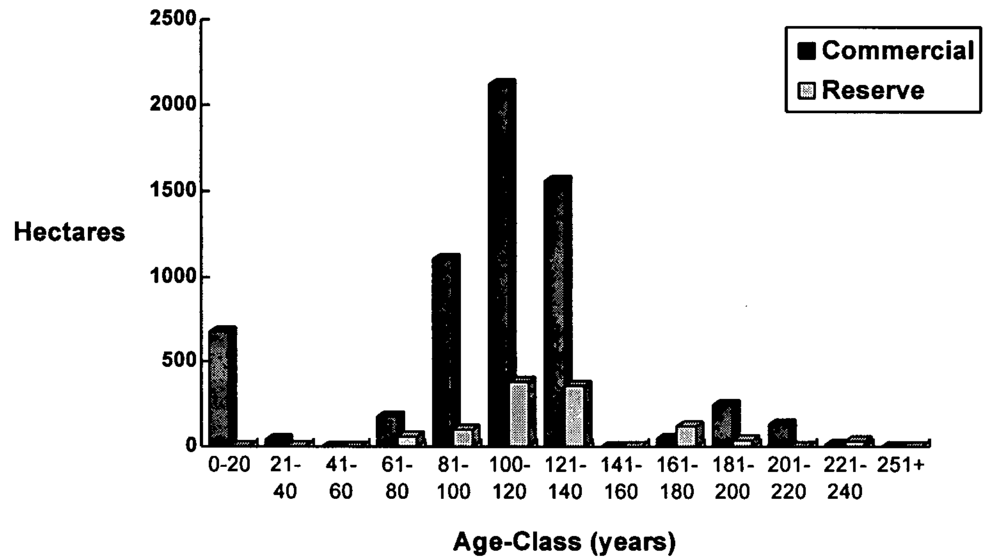

Figure 3-6. Initial age-class distribution in the Nehaliston Creek Watershed. Commercial stands are eligible for harvesting, whereas reserved stands are not.

Table 3:2. Summary of harvest rules and the area to which each applies for the Nehaliston Creek watershed. Hectares affected by each rule are categorized as commercial and reserved.

Rule	Greenup Period (years)	Max. Age for Early Seral Stage (years)	Max. % of Zone Area in Early Seral Stage	Minimum Mature Age (years)	Min. % of Zone Area in Mature Seral Stage	Hectares Affected	
						Commercial	Reserved
TIMBER	19	19	30	50	20	**6,390**	**842**
TOTAL						**6,390**	**842**

Data for the Nehaliston Creek watershed were originally prepared by the Forest Engineering Research Institute of Canada (FERIC). To facilitate the modeling process, the relatively small harvest units designed by FERIC were aggregated by the Forest

Operations Research Group at UBC to form 353 polygons with an average size of 29 hectares, ranging from 0.5 ha. to 252 ha..

3.4.2 Corridor Modeling Methods

The methods used to model each of the three corridors and the accompanying timber supply and road network projections for both the Hardwicke Island and the Nehaliston Creek Watershed forests are described below. For the most part, the approaches used for both forests are identical, with exceptions as noted.

3.4.2.1 FEN Types and Modeling Techniques

A total of 6 simulations were done for each forest: 1) a base case with no FENs (BASE); 2) a fixed corridor case (FIX); 3) a replacement corridor case (REP); 4), 5), and 6) consist of 3 different floating corridor cases (FLT-1, FLT-2, FLT-3). The codes and descriptions of each case are shown in Table 3:3.

Table 3:3. Summary of the codes and corridor-type, planning horizons, and cost curve shape used to model each of the six corridors for the Hardwicke and Nehaliston case studies. Each case was simulated for fifteen 10-year periods.

Case	Code	Description	
1	BASE	No Corridors	
2	FIX	Fixed Corridor	
3	REP	Replacement Corridor	
		Minimum Corridor Age:	Hardwicke – 80 years
			Nehaliston – 100 years
4	FLT-1	Floating Corridors; Parabolic Cost Curve	
5	FLT-2	Floating Corridors; Asymmetric Parabolic Cost Curve	
6	FLT-3	Floating Corridors; Step Function Cost Curve	

The BASE case contains no FEN, and is used as a basis for comparison. The harvest simulation consisted of fifteen 10-year periods with all harvests occurring at the end of each period. In this, and all the remaining cases, target harvest volumes were adjusted so that the area treated in each period remained constant. Since Hardwicke Island contains some residual old-growth stands, and fast-growing, second-growth stands are harvested on short rotations, the initial target harvest level was reduced by 10% per decade until long-term yield was reached in the fourth period. For the Nehaliston forest, an even-flow of volume over time was chosen as a result of the relatively slow growth rates. Lastly, when an acceptable harvest schedule was found, the necessary road network was scheduled.

For the fixed corridor case, a series of contiguous harvest units which provide upslope and riparian connectors were identified for each forest, and were permanently reserved from future harvesting (Figure 3-7). A 150-year harvest simulation was applied to the residual forest. In the case of the Hardwicke Island forest, an initial scarcity of stands meeting the minimum age requirement for the corridor resulted in the need to "recruit" stands which would become suitable for the corridor over time. However, this was not the case in Nehaliston, as an abundance of mature stands are present and the corridor was easily identified.

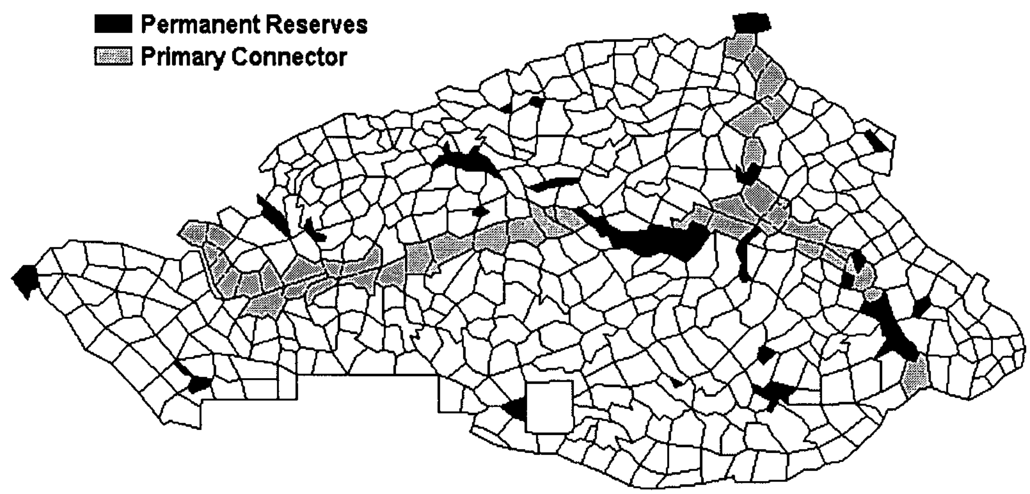

Figure 3-7. Location of the permanent connector used to model the FIX corridor case. Permanently reserved stands outside of the corridor are also shown.

Replacement corridors were designed by adding a second corridor to the one designed for the FIX case (Figure 3-8). In an attempt to maximize harvest volumes, harvesting occurs in the primary corridor during the first period of the simulation in Hardwicke, while the older secondary corridor remains intact. An 8 period (80-year) moratorium is then imposed to allow the primary corridor to reach the minimum required age. The secondary corridor is then harvested for 3 periods (periods 9 -12) while the primary corridor serves as the connector. A moratorium is then placed on both corridors for the remaining 3 periods of the simulation. In Nehaliston, harvesting occurs in the primary corridor over the first 3 periods, followed by a 10 period (100-year) moratorium. Harvesting then occurs for the remaining two periods of the planning horizon in the secondary connector.

Table 3:4 summarizes the harvest sequence in the primary and secondary corridors for each forest.

Table 3:4. Sequence of harvesting (H) and imposed moratoriums (-) used to model the replacement corridors on Hardwicke Island and the Nehaliston Creek watersheds.

Forest	FEN type	Period														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hardwicke	1°	H	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2°	-	-	-	-	-	-	-	-	-	H	H	H	-	-	-
Nehaliston	1°	H	H	H	-	-	-	-	-	-	-	-	-	-	-	-
	2°	-	-	-	-	-	-	-	-	-	-	-	-	-	H	H

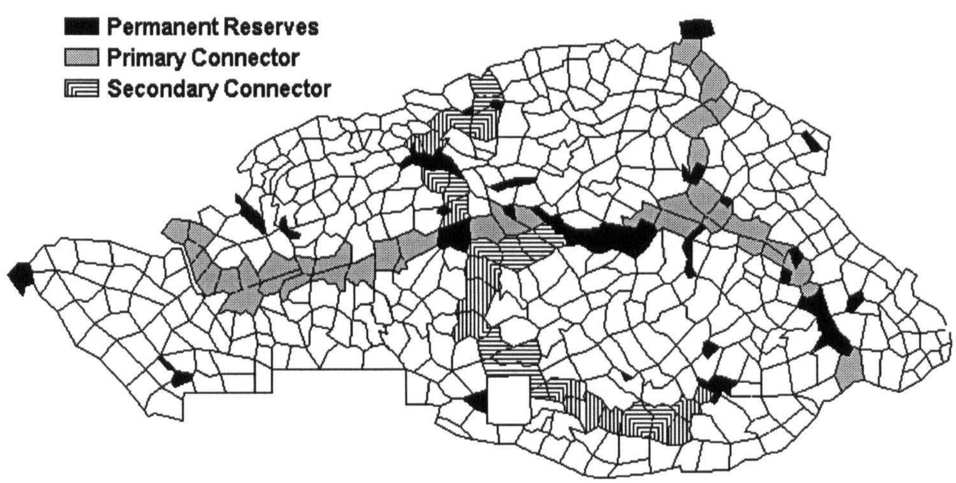

Figure 3-8. Primary and secondary connectors used to model the replacement corridor case. The primary corridor is identical to that used in the FIX case. Permanently reserved areas outside of the FEN are also shown.

For the floating corridors, an arbitrary subset of the permanently reserved polygons was chosen and designated as the critical habitat islands around which the corridor would be designed (Figure 3-9). The modified minimum Steiner tree heuristic algorithm described earlier was used to identify the set of contiguous harvest blocks that generate the spanning tree on the habitat island polygons, thus creating the corridor of mature timber. The minimum common edge between adjacent polygons is set at 150m for Hardwicke and 200m for Nehaliston.

Three cost curves were used to demonstrate the different responses of the model (Figure 3-10). In general, the first cost curve is parabolic in form, and tends to select strongly for stands that are no more than 20 years older than the minimum corridor age, with no preference given to younger or older stands in the absence of the preferred-age stand. The second cost curve form is asymmetric parabolic, and preferentially selects stands that are older than the preferred age class, rather than younger. The third cost curve is a linear step function that selects strongly for stands that are beyond the minimum corridor age-class. All permanently reserved polygons are eligible to be included in the corridor at essentially no cost, regardless of their age.

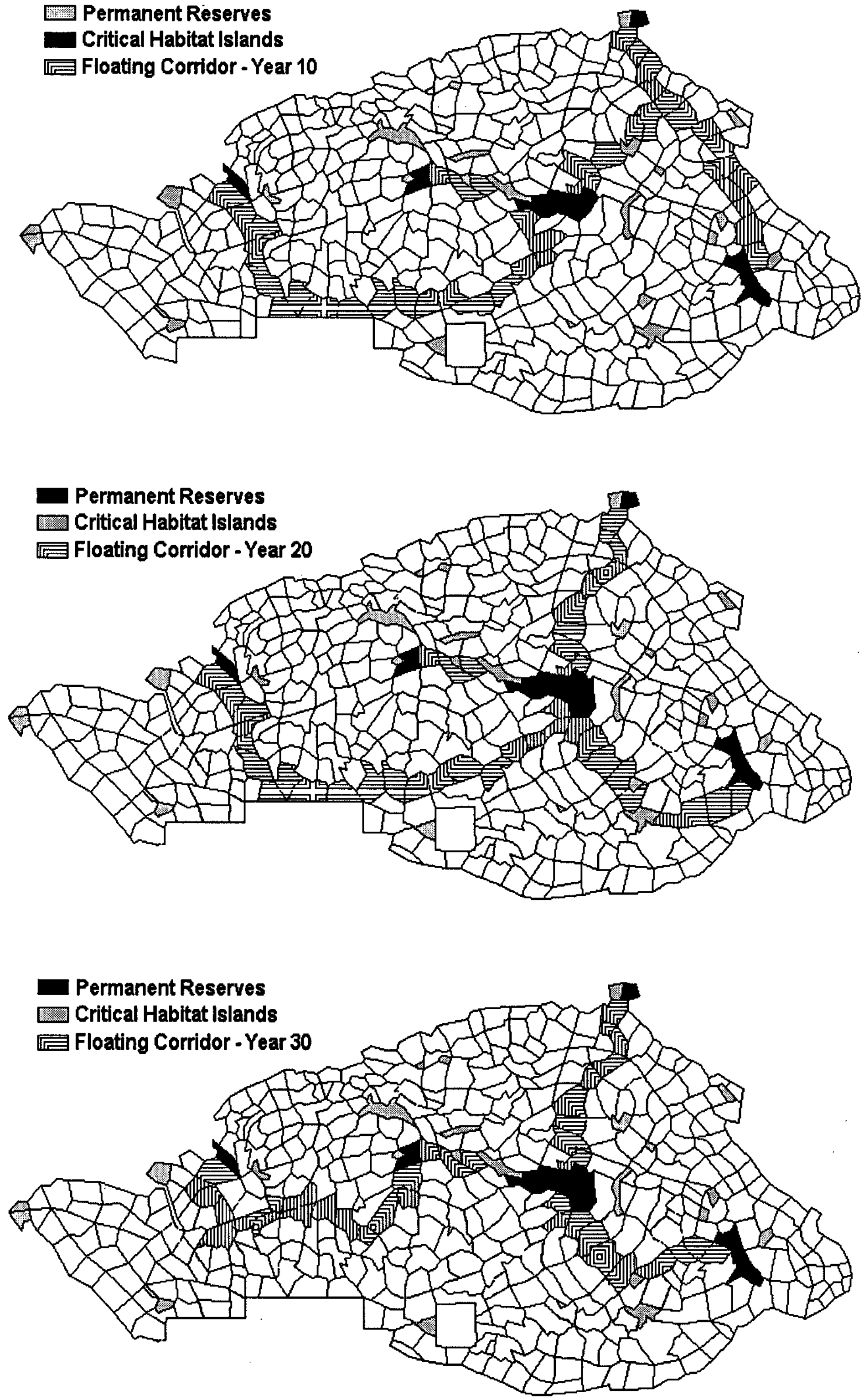

Figure 3-9. An example of the floating corridor dynamics from the Hardwicke Island case study area. The critical habitat islands are linked by a floating corridor of mature stands. Other permanently reserved areas not incorporated in the FEN are also shown.

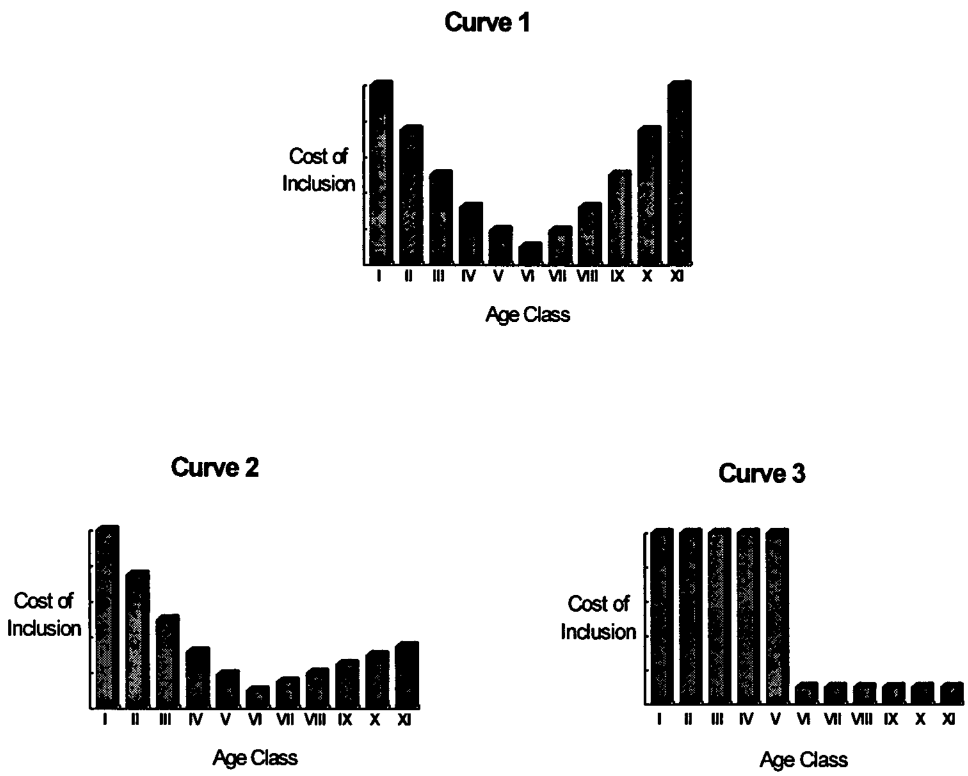

Figure 3-10. General shape of cost curves used to model the floating corridors. Curve 1 selects stands near the minimum age, Curve 2 is similar to Curve 1, but allows older stands to enter the FEN at a low cost. Curve 3 selects stands older than the minimum age, with no preferential selection of age-class.

3.4.3 Results and Discussion

Results for the six cases using both forests are presented below. The reductions in harvested area and harvested volume for each connector type will first be compared, followed by a similar comparison of the area harvested in each case. Then, descriptive statistics regarding the corridors developed in each case are presented. Finally, the difference in road network activity is discussed.

3.4.3.1 Hardwicke Island

3.4.3.1.1 Areas Treated

Reductions in harvested area relative to the BASE case vary among the five cases. As expected, the reductions in the overall area treated in each period (harvested hectares) is highest for the replacement corridors – an average of 13% reduction relative to the BASE case – due to the additional area that is required for the secondary corridor. The floating corridor case, FLT-2, shows a substantial reduction of 12% in the short-term (0-20 years). FLT-1, on the other hand, results in a relatively constant reduction of 11% throughout the planning horizon. Finally, the least reduction in harvested area (4% - 6%) is attained using the floating corridor, FLT-1.

Table 3:5. Reductions in harvested areas for Hardwicke Island for each FEN modeling technique. Reductions are expressed as a percentage of the areas harvested in the BASE case.

Term	FIX	REP	FLT-1	FLT-2	FLT-3
Short (0-20)	3	8	11	12	4
Medium (21-80)	7	14	11	6	6
Long (81-150)	6	13	10	8	4
TOTAL	6	13	11	8	4

3.4.3.1.2 Harvest Volumes

Percent reductions in harvest volumes relative to the BASE case for each of the six cases are presented in Table 3:6. Reductions in total harvest volumes for the 150-year planning horizon are highest for the replacement corridor, and lowest for the floating corridor, FLT-3. The extended rotations associated with the replacement corridors lead to a substantial reduction in mean annual increment, and hence a reduction in long-term yield (minimum rotation = 20 years harvest in Primary + 80 years growth in Primary + 20 years harvest in secondary + 80 years growing Secondary = 200 years rotation). A more complete explanation of this concept can be found in Nelson and Shannon (1994). Short-term (0-20 years) reductions are most pronounced in the floating corridors, FLT-1 and FLT-2 (12% and 13%, respectively). Because the historic harvest patterns are not conducive to corridor establishment, the blocks best-suited for corridors are those that are available for immediate harvest. Since the corridor is designed prior to the harvest schedule, these blocks are incorporated in the corridor. Reductions in the remainder of the planning horizon are similar for the fixed and the floating cases, ranging from 5% - 7%, with the exception of FLT-1, which has a medium-term (21- 80 years) reduction of 11%.

The similarity in reductions in harvest volumes among cases can be attributed to the restrictive nature of the harvesting guidelines that are in place. A substantial portion of the land base (33%, Table 3:1) is constrained to having 5% or less of the zone area in the early seral stage. This leads to large areas of unharvested forest which can either be used to provide connectors, or can yield high harvest volumes throughout the planning horizon.

Table 3:6. Reductions in harvested volumes for Hardwicke Island for each corridor modeling technique. Reductions are expressed as a percentage of the volume harvested in the BASE case.

Term	FIX	REP	FLT-1	FLT-2	FLT-3
Short (0-20)	3	8	12	13	6
Medium (21-80)	7	13	11	7	6
Long (81-150)	6	10	7	7	5
TOTAL	6	11	9	8	6

3.4.3.1.3 Corridor Composition

The percent area of the forest that is occupied by the corridors for each case is shown in Table 3:7. The fixed (FIX) and replacement (REP) occupy a fixed proportion of the land base over time. The primary and secondary corridors used to model the replacement corridors occupy 8% and 11% of the forest, respectively. The floating corridors occupy between 9% and 13% of the land base, and therefore, consist of slightly more area than the corridors designed for the FIX case. The closeness of the approximation of course, depends on the number, and geographic location of habitat islands identified by the user. Obviously, selecting fewer habitat islands in closer proximity to each other would lead to a smaller proportion of the land base in corridors.

Table 3:7. Percentage of the working forest land base set aside for corridors for the Hardwicke Island study area. The figures do not include permanently reserved areas which may have been incorporated in the FEN.

Term	FIX	REP	FLT-1	FLT-2	FLT-3
Short (0-20)	9	19	13	13	13
Medium (21-80)	9	19	12	13	12
Long (81-150)	9	19	10	12	9
TOTAL	9	19	11	12	11

Average ages for a single hectare of the corridor are calculated by the sum of the hectares in a given age-class multiplied by the age-class midpoint, and dividing by this product by the total hectares in the corridor. Permanently reserved polygons and critical habitat islands are not included in this calculation so that the calculation reflects the average age of polygons which would otherwise be considered to be part of the working forest land base. The average periodic age of one hectare in each of the corridors is shown in Figure 3-11.

It can be seen that for the FIX, REP(1), and the FLT-1 cases, the average age of one hectare increases linearly with time. In contrast, the average age of one hectare in the FEN for the remaining cases increases until the 8th or 10th decade, then begins to decrease with time. In particular, the FLT-1 case results in an average age of not more than 120 years, while the FLT-3 corridor appears to level off at 140 years. By maintaining a younger age in the corridor, the older stands are then made available for harvest in subsequent periods; however, additional stands may need to be reserved in order to ensure that seral stage requirements for the remaining forest have been met.

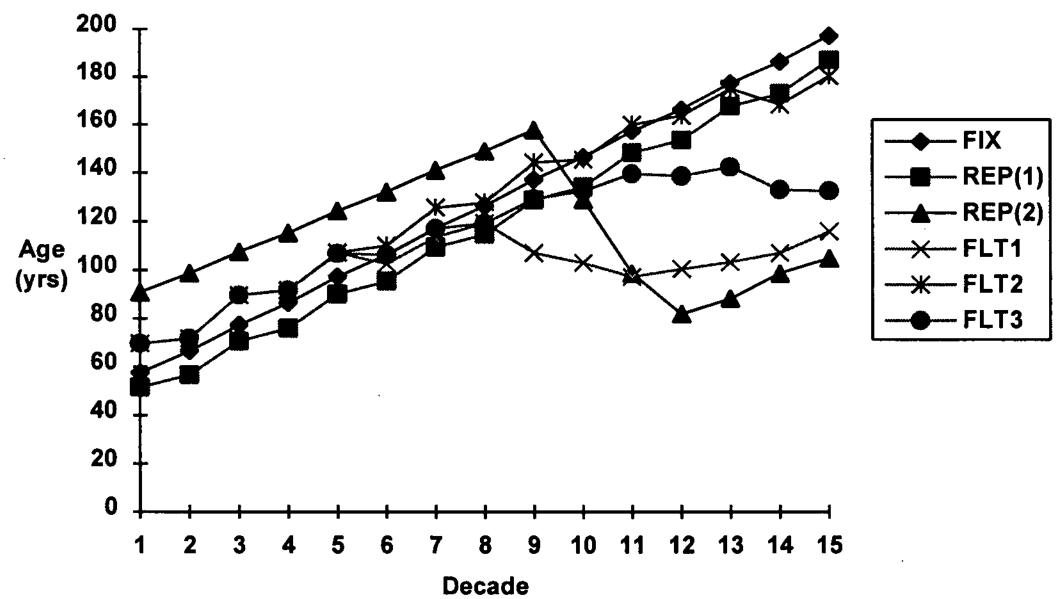

Figure 3-11. Average age in years of one hectare in the corridor for Hardwicke Island. The average age of both the primary and secondary components of the replacement corridor are shown as REP(1) and REP(2) respectively.

3.4.3.1.4 Road Network

Changes in the total length of active road for each case were similar for all cases and all time frames analyzed. Reductions in active road length relative to the BASE case ranged from 3% – 6% for all cases, with no specific trends associated with any one of the corridor types.

3.4.3.2 Nehaliston Creek

3.4.3.2.1 Areas Treated

The reduction in the areas treated (harvested) for each of the cases is shown in Table 3:8. Reductions for the FIX, and REP cases are relatively constant over the planning horizon at approximately 4% and 19%, respectively. Reductions for the REP case are well pronounced as a result of the long rotations (240 years minimum), and the significant proportion of the working forest that is removed from the commercial land base for extended periods of time. On the other hand, the floating corridors result in reductions ranging from 1% to 8%, with the short-term reductions in the range of 6%- 8% of the BASE case.

Table 3:8. Reductions in harvested areas for the Nehaliston watershed for each corridor modeling technique. Reductions are expressed as a percentage of the areas harvested in the BASE case.

Term	FIX	REP	FLT-1	FLT-2	FLT-3
Short (0-20)	4	19	6	6	8
Medium (21-80)	5	19	2	6	6
Long (81-150)	4	21	1	5	2
TOTAL	4	20	2	6	4

3.4.3.2.2 Harvest Volumes

Harvest levels in the Nehaliston forest generally increased as a result of the substitution of dynamic corridors for the permanent or replacement corridors as shown in Table 3:9. Substantial reductions (19%-20% of BASE) resulted when the replacement corridors were used, again due to the additional area required, as well as the extended rotations in both the primary and secondary corridors. The fixed corridor case, FIX, resulted in a reduction of 5% - 6% of the BASE case harvest throughout the planning horizon, as opposed to a 3% - 5% reduction in each of the FLT-# cases. The exception is the short-term reduction of 8% in the FLT-3 case, resulting from the inclusion of older, high volume-per-hectare stands in the corridor in the first and second periods of the simulation. However, as a result of the cost curves used to select polygons for the corridors in FLT-1 and FLT-2 (Figure 3-10), older stands are not selected as often in these two cases.

Overall reductions are lower than those noted for Hardwicke Island due to the comparatively relaxed nature of the harvesting guidelines (Table 3:2), and the abundance of stands available for harvesting in the early part of the planning horizon (Figure 3-6).

Table 3:9. Reductions in harvested volumes for the Nehaliston watershed for each corridor modeling technique. Reductions are expressed as a percentage of the volume harvested in the BASE case.

Term	FIX	REP	FLT-1	FLT-2	FLT-3
Short (0-20)	6	20	5	5	8
Medium (21-80)	5	19	2	4	5
Long (81-150)	6	20	0	5	3
TOTAL	6	20	2	5	4

3.4.3.2.3 Corridor Composition

The percent of the working forest area that is comprised of corridors is shown in Table 3:10. Areas set aside for corridors comprise approximately 8% – 11% for all but the REP case, which is comprised of 10% primary corridor, and 9% secondary corridor. These percentages show that the floating corridors can closely approximate the area in the FIX corridor case.

Though the floating corridors cover the same or larger percentage of the working forest land base than does the fixed corridor, higher harvest volumes are attained for the FLT-# cases in Nehaliston. Permitting stands to enter and leave the corridor through time, makes these stands available for harvest in the later periods of the simulation. In contrast to Hardwicke Island, the relaxed nature of the harvest constraints in Nehaliston allows almost all stands to be treated during the planning horizon, thereby leading to higher, overall volume returns.

Table 3:10. Percentage of the working forest land base that is set aside for corridors in the Nehaliston watershed. Permanently reserved areas which may have been incorporated in the FEN are not included as part of the corridor area.

Term	FIX	REP	FLT-1	FLT-2	FLT-3
Short (0-20)	9	19	9	9	8
Medium (21-80)	9	19	8	8	9
Long (81-150)	9	19	11	10	9
TOTAL	9	19	10	9	9

Average ages for one hectare in the corridors are shown in Figure 3-12. Similar to Hardwicke Island, the average age in the FIX, REP(1), and the FLT-3 cases shows a linear increase over time. In FLT-3, nearly all the stands selected for the corridor in the first period remain in the FEN for the entire planning horizon. REP(2) also shows a linear increase over time, with the exception of the last 2 periods when harvesting occurs. The remaining cases, FLT-1 and FLT-2, utilize cost curves that favour the selection of younger stands for the corridor, thereby causing the corridor to actively move across the landscape over time, and result in the average age reaching a maximum of 150 - 160 years in decades 7 and 9, respectively.

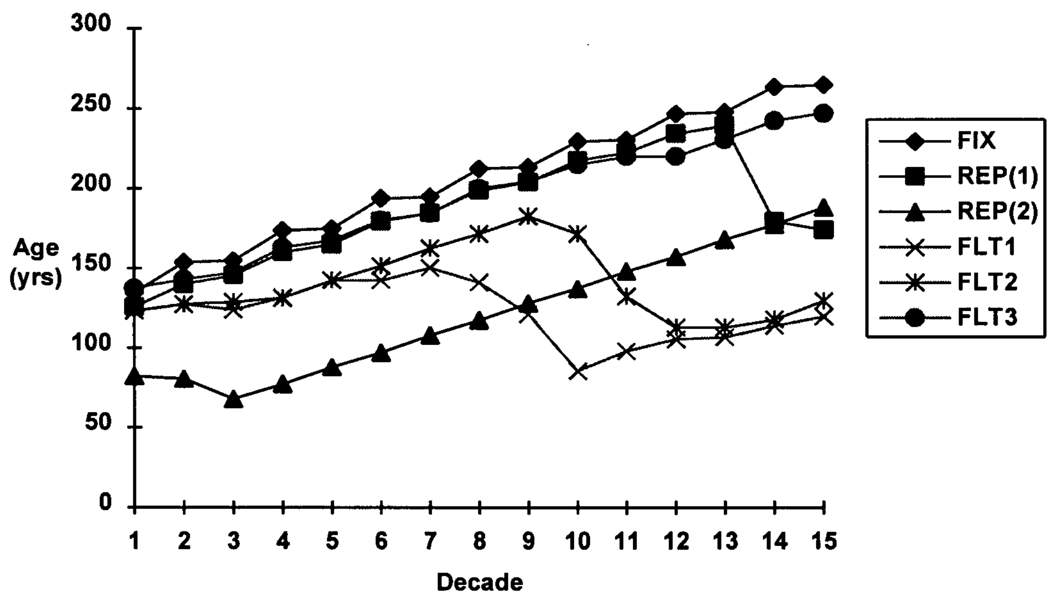

Figure 3-12. Average age in years of one hectare in the corridor for the Nehaliston watershed. The average age the primary and secondary corridors designed for the replacement corridor case are shown as REP(1) and REP(2), respectively.

3.4.3.2.4 Road Network

Total length of active roads for the Nehaliston forest generally increased relative to the BASE case (Figure 3-13). Both the FLT-1 and FLT-2 cases showed short-, medium-, and long-term increases ranging from 100% – 105% of BASE. The REP case, however, showed a substantial increase in short-term road activity (120% of the BASE case). Because more land is reserved for the two corridors, polygons available for harvest in the early periods are located further away than in the BASE case, resulting in increased road activity. Medium- and long-term averages of 85% and 90% of BASE, respectively are directly proportional to the reduction in harvested volume over these two terms.

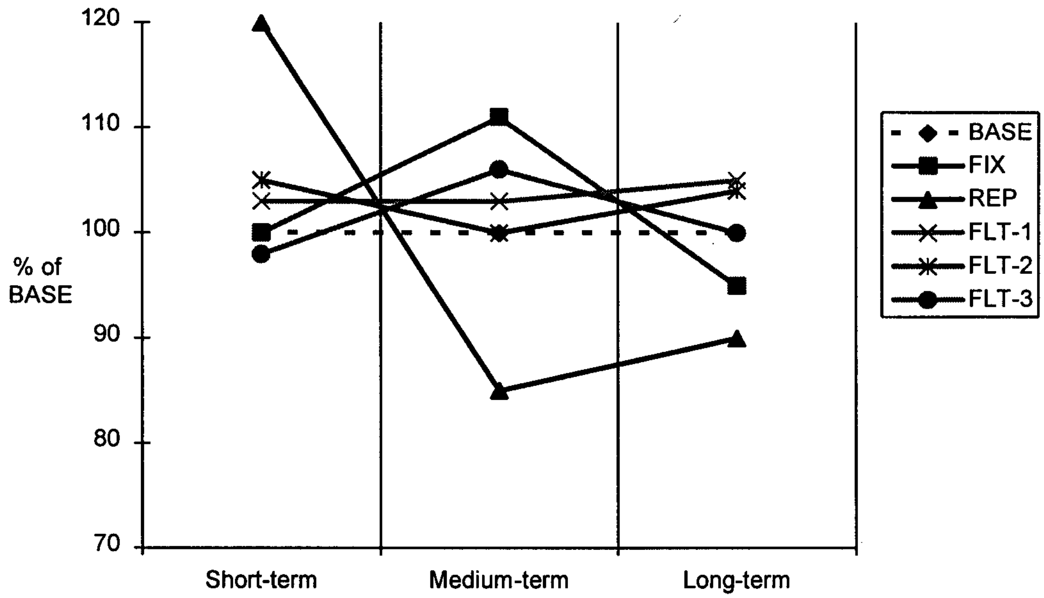

Figure 3-13. Changes in the total length of active roads for the Nehaliston forest relative to the BASE case (dashed line).

Generalizations about the effect of each corridor type on road network activity should be made with caution. Changes from the BASE will obviously depend on the location and extent of the road network required to access blocks treated in each period. Hence, results will likely vary from among forests.

3.5 Conclusions

By adjusting the cost curves used to select polygons, the floating corridors can be designed to yield results that meet user defined age-class objectives and allow for improved timber supply projections for loosely constrained forests. However, it appears that the fixed corridors may be adequate for modeling areas where harvesting opportunities are limited, especially when tight early seral stage objectives for the landscape unit are defined. The nature of the harvesting rules applied appears to also govern road activity. Regardless of the corridor modeling technique, road activity decreases proportionally to timber supply for the tightly constrained case. However, fixed and floating corridors in the loosely constrained case cause road activity to increase. Finally, while replacement corridors are intuitively attractive, their inclusion results in substantial reductions in harvest volume. This reduction stems from the additional area required to design these connectors, as well as the extended rotations for stands which comprise the two corridors. Finally, replacement corridors may be accompanied by increased road activity in the short-term.

The connectors developed by the floating corridor algorithm are similar in age-class structure and percent of area occupied to the expert-designed permanent corridors used for Hardwicke Island study. Furthermore, the algorithms used in this study are fast enough to allow several policy options to be evaluated in a reasonable period of time. Approximately 8 hours were required to set up the fixed, replacement, and the three floating corridor scenarios, and to subsequently project the 150-year harvest schedules for Hardwicke Island.

Chapter 4

Conclusions

4.1 Summary

In this thesis, I described briefly the three general hierarchical levels of forest planning, the two basic types of models used to address forest planning problems, and presented two problems which can only be addressed through the use of spatially explicit harvest scheduling models.

For the sustained yield unit size problem, a series of aggregations was performed to create sequentially larger sustained yield units for which timber supply and other indicators were summed, reported, and compared for total of the units across the entire area. I showed that total harvest volumes for the timber supply area used in this study would not be substantially impacted until the constituent units are reduced to approximately one-fourth of the size of the current TSA. I also demonstrated that the timing and intensity of harvests in individual units can vary considerably depending on the size of the sustained unit, and indicated some of the potential implications of this variability.

The corridor analysis problem was solved by defining three types of corridors, and comparing impacts on timber supply and corridor structure for each technique. I demonstrated the floating corridor problem using a series of shortest path algorithms to connect critical habitat islands during each period of the harvest scheduling simulation. I further showed that the impacts associated with each corridor type depend largely on the nature of the harvesting guidelines that are in place.

4.2 Future Research

4.2.1 Sustained Yield Unit Size

The sustained yield unit size problem is an important and current issue. This study should be repeated on additional areas in order to better identify trends in the indicators. Conversely, altering the initial age-class structure, and harvest priorities may provide further information as to the effects of forest combination. Further analysis of the spatial distribution of the harvest patterns generated for each level of aggregation may reveal impacts on wildlife, hydrology, or other issues which are not apparent at this time. In addition, simulations in which harvest constraints relating to opening size, greenup periods, and minimum harvest levels are changed should be performed in order to alter the spatial and temporal distribution of harvests. In doing so, guidelines could be designed to maintain the desired level of timber supply while permitting temporary closure of selected watersheds.

4.2.2 Corridor Analysis

The corridor analysis study is intended to demonstrate the practicality of the floating corridor concept, and to provide a framework for incorporating the algorithms into harvest scheduling models. For that reason, age and common edge length between adjacent polygons were the only criteria used to select blocks for inclusion in the corridor. However, additional stand attributes such as slope and aspect of the blocks could easily be integrated into the cost of inclusion. Alternatively, a simple weighting of "costs" associated with each attribute (say 50% based on age, 35% on average slope, and 15% on aspect) may be sufficient to design corridors.

A considerably more elegant method of choosing corridor polygons would involve an evaluation of the harvest guidelines in each zone, and calculating a cost based on the amount of slack in the constraints for that zone. This could direct the corridor to move into areas in which harvesting activities are already constrained by other non-timber resource objectives.

The corridor study did not consider uneven-aged management either in the FEN, or in the remainder of the forest. Additional field research is needed in order to determine the extent to which partial harvesting could take place within the FENs, and the amount of alteration that can be withstood before the desired attributes are lost from the constituent stands. Once this information is available, implementation of partial harvesting systems within the FEN boundary may alleviate negative impacts on timber supply.

References

BAZAARA, M. S. and R. W. LANGLEY 1974. A Dual Shortest-Path Algorithm. SIAM Appl. Math., 26(3):496-501.

BERTSEKAS, D. P. 1991. Linear Network Optimization – Algorithms And Codes. The MIT Press, Cambridge, MA. 359 pp.

B.C. MINISTRY OF FORESTS 1986. Forest insect and disease impacts in Timber Supply Areas. Pest Management Report #6. Protection Branch, Victoria, B.C.

B.C. MINISTRY OF FORESTS 1991. Review of the timber-supply analysis process for B.C. timber supply areas. Victoria, B.C. 43 p.

B.C. MINISTRY OF FORESTS 1992. Guidelines To Maintain Biological Diversity In Coastal Forests. B.C. Ministry of Forests, B.C. Ministry of Environment, Lands, and Parks. Victoria, B.C. 30 pp.

B.C. MINISTRY OF FORESTS 1993. Revelstoke TSA—Timber Supply Analysis. Integrated Resources Branch, B.C. Ministry of Forests. Victoria, B.C. 60 p.

B.C. MINISTRY OF FORESTS 1993a. British Columbia Forest Practices Code — Rules. B.C. Ministry of Forests, Victoria, B.C. 128 pp.

B.C. MINISTRY OF FORESTS 1995. (in prep.) Biodiversity Field Guide. B.C. Ministry of Forests, Victoria, B.C.

BROOKS, D.J. and G.E. GRANT 1992. New Perspectives In Forest Management: Background, Science Issues, And Research Agenda. USDA For. Serv. PNW-RP-456. 17pp.

BURTON, P.J., A.C. BALISKY, L.P. COWARD, S.G. CUMMING, and D.D. KNEESHAW 1992. The Value Of Managing For Biodiversity. For. Chron., 68(2):225-237.

DAVIS, L.S., AND K. N. JOHNSON 1987. Forest Management. Third Edition. McGraw-Hill, Inc. New York. 790 p.

DEO, N. and C. PANG 1984. Shortest Path Algorithms: Taxonomy And Annotation. Networks, 14:275-323.

DIJKSTRA, E. 1959. A Note On Two Problems In Connexion With Graphs. Numerische Mathematik, 1:269-271.

EASTMAN, D.S. 1978. Habitat selection and use in winter by moose in sub-boreal forests of north central British Columbia and relationships to forestry. Ph.D. Thesis, Faculty of Forestry, University of British Columbia, Vancouver, B.C.

FRANKLIN, J.F. 1993. Preserving Biodiversity: Species, ecosystems, or landscapes?. Ecol. Appl., 3(2) pp. 202-205.

HARRIS, L.D. 1984. The Fragmented Forest, Island Biogeography Theory And The Preservation Of Biotic Diversity. Univ. Chicago Press, Chicago, Ill. 211 pp.

HUNTER, M.L. Jr. 1990. Wildlife, Forests, And Forestry. Principles Of Managing Forests For Biological Diversity. Prentice Hall, Inc. New Jersey. 370 pp.

HWANG, F. K. and D. S. RICHARDS 1992. Steiner Tree Problems. Networks, 22:55-89.

KANGAS, J. and J. KUUSIPALO 1993. Integrating Biodiversity Into Forest Management Planning And Decision Making. For. Ecol. and Manage., 61:1-15.

LI, H. 1989. Spatio-temporal pattern analysis of managed forest landscapes: a simulation approach. Dissertation, Oregon State University, Corvallis, Oregon.

NELSON, J.D, T. SHANNON AND D. ERRICO 1993. Determining the effects of harvesting guidelines on the age-class profile of the residual forest. Can. J. For. Res. 23: 1870-1880.

NELSON, J.D. and T. SHANNON 1994. Timber Supply Assessment Of Biodiversity Guidelines In British Columbia. Paper presented at the IUFRO Conference, Northeast Forestry University, Harbin, Peoples Republic of China, July 1994.

NELSON, J. D., M. HAFER, T. SHANNON, AND D. GIZOWSKI 1994. ATLAS : A Tactical Landscape Analysis System V1.3. User's Manual. Forest Operations Research Group, Department of Forest Resources Management. Faculty of Forestry, University of British Columbia. Vancouver, B.C..37p.

O'HARA, A.J., B.H. FAALAND, AND B.B. BARE 1989. Spatially constrained timber harvest scheduling. Can. J. For. Res. 19:715-724.

PEARSE, P. H. 1976. Timber rights and forest policy in British Columbia. 2 vols. Report of the Royal Commission on Forest Resources. Victoria, B.C.

PRANCE, G.T. 1990. Consensus for conservation. Nature, vol. 345, May 31. p. 384.

ROST, G.R., AND J.A. BAILEY 1979. Distribution of mule deer and elk in relation to roads. Journal of Wildlife Management **43**(3):634 - 641.

SAF 1991. Society of American Foresters. Task Force Report on Biological Diversity in Forest Ecosystems. SAF, Behesda, Maryland. 52 pp.

SALOWE, J. S. and D. M. WARME 1995. Thirty-Five Point Rectilinear Steiner Minimal Trees In A Day. Networks, 25:69-87.

SCHOONMAKER, P. and A. McKEE 1988. Species Composition And Diversity During Secondary Succession Of Coniferous Forests In The Western Cascade Mountains Of Oregon. For. Sci., 34:960-979.

SESSIONS, J. 1992. Solving For Habitat Connections As A Steiner Network Problem. For. Sci., 38(1):203-207.

SESSIONS, J. AND J.B. SESSIONS 1992. Post-New Forestry Tools for Tactical Forest Planning. Western Wildlands, Winter 1992. pp. 39-44.

SMITH, D. K. 1982. Network Optimization Practice – A Computational Guide. Ellis Horwood Limited, Chichester, West Sussex, England. 237 pp.

STEVENSON, S.K., AND D.F. HATLER 1985. Woodland caribou and their habitat in southern and central British Columbia. Land Management Report, ISSN 0702-9861; no. 23. BC Ministry of Forests, Victoria, B.C. 112p.

WALLIN, D.O., SWANSON, F.J., AND B. MARKS 1994. Landscape pattern response to changes in landscape pattern generation: Land-use legacies in forestry. Ecological Applications, 4(3), pp. 569-580.

WARD, A.L. 1975. Elk behavior in response to timber harvest operations and traffic on the Medicine Bow Range in south-central Wyoming. In Proc. of the Elk-Logging-Roads Symp. Moscow, Idaho. pp. 32-43.

WILLIAMS, B.L., and B.G. MARCOT 1991. Use Of Biodiversity Indicators For Analyzing And Managing Forest Landscapes. Trans. 56th N. A. Wildl. & Nat. Res. Conf.. pp. 613-627.

WINTER, P. 1987. Steiner Problems In Networks: A Survey. Networks, 17:129-167.