WORKING PAPER
1998-11

sustainable forest management network

réseau sur la gestion durable des forêts

Using Forest Fire Hazard Modelling in Multiple Use Forest Management Planning

W.A. Thompson, I. Vertinsky, H. Scheier, and B.A. Blackwell

A Network of Centres of Excellence
Un réseau de centres d'excellence

For copies of this or other SFM publications contact:

Sustainable Forest Management Network
G208 Biological Sciences Building
University of Alberta
Edmonton, Alberta, T6G 2E9
Ph: (780) 492 6659
Fax: (780) 492 8160
http://www.biology.ualberta.ca/sfm

Using Forest Fire Hazard Modelling in Multiple Use Forest Management Planning

by

William A. Thompson[*]

Ilan Vertinsky[*]

Hans Schreier[+]

and

Bruce A. Blackwell[**]

[*] Forest Economics and Policy Analysis Research Unit, University of British Columbia, Vancouver
[+] Resource Management and Environmental Studies, University of British Columbia, Vancouver
[**] B.A. Blackwell and Associates, North Vancouver

ABSTRACT

Concerns about fire in North American forest management are shifting from a strict focus on fire prevention to a broader view which considers fire accommodation and fire emulation as management alternatives. There is a substantial gap between the articulation of general principles of fire accommodation and fire emulation and their operational application. In this paper we describe a forest modelling system and examine several alternative operational interpretations of the accommodation and emulation of fire. A key element in the modelling system is a forest fire hazard model which estimates the potential for forest fire based upon forest attributes, forest utilization and topography. The modelling system was applied to a 24,000 hectare forest in a montane watershed in Southeastern British Columbia. Three forest management plans based upon the fire accommodation and emulation principles were compared with five more traditional management plans. The comparisons involved the net present values of timber harvests, timber harvest volumes, degrees of fire hazard, impacts on forest biodiversity, and the number of violations of two common regulatory constraints — even flow maintenance and green-up and adjacency restrictions. Large differences in net present value, forest biodiversity and fire hazard were found among the alternative management approaches.

INTRODUCTION

Fire has been a major force in shaping the landscape of Canada. Prior to European settlement, many Canadian forest ecosystems were maintained and renewed by wildfire. With the early settlers came fire management. Initially, fire was used extensively in the conversion of forestland to farmland and pasture (Stocks and Trollope 1993). By the early 1900s, the introduction of European forestry principles to forest management led to a shift in the practice from using fire for maintenance of woodlands to the suppression of fire (Pyne 1990). Over the past century human intervention has changed the structure of many Canadian forests by altering the frequency and severity of fires. Combined with timber harvesting and pest management, fire detection, prevention and suppression activities have altered the natural patterns of forest destruction and renewal. Forests whose structure and diversity depended upon fire to produce a mosaic of successional types are now highly susceptible to severe fires (Heinselman 1973; Foster 1982). With fewer fires to maintain the natural mix of forest ecosystems and successional stages, the ecological structure of the managed forest has been shifted to one with more mature forest stands, greater mass of fuel and, consequently, higher risk of catastrophic fire.

Over the past thirty years, evidence has accumulated that total fire exclusion is neither economically feasible nor ecologically desirable (Stocks and Trollope 1993). This has led to a shift in fire management strategies from the simple suppression paradigm to an array of paradigms, ranging from fire detection, prevention and suppression in areas of extreme risk to life and property, such as urban-rural interfaces, to a focus on economic efficiency of fire protection for timber resources, to fire accommodation or acceptance in maintenance of natural ecosystems. A parallel shift in thinking about forest insect pests has taken place in Canadian forest management. For example, MacLean and Porter (1994) identified a management need for tools to both predict occurrence and impacts of budworm outbreaks on forest resources and plan forest management treatments to reduce the risk or potential severity of future outbreaks. Managing a forest to reduce the risk of insect devastation is an example of a risk management strategy aimed at reducing the vulnerability of resource values to uncertainty. It is closely akin to increasing the resilience of the forest to environmental variability (Clark 1980; Holling 1981, 1984; Brumelle et al. 1990) and need not result in poor economic performance (Thompson et al. 1979). There are many other approaches to forest risk management, but they will not be considered here (see reviews in Brumelle et al. 1990; Hof 1993; Boychuk and Martell 1996).

With the current shift in forest management paradigm away from a fire prevention mode, a fire accommodation or emulation approach (Kilgore 1973) has been gaining currency (Whelan 1995). While some have argued that in ecosystems which depend upon fire to maintain their structure and diversity, managers should 'let it burn', a review of the Yellowstone fire and its aftermath (Christensen et al. 1989) suggested that a blend of fire suppression and management practices to mimic fire effects would be most appropriate. Examples can be found in a guide for private forestland owners (Swedish Board of Forestry 1990), which advises the application of ecological principles to woodlot management, moulding harvest practices to imitate the path of fire in order to promote both natural conservation and timber production.

Fire emulation management is generally perceived as an imitation of pre-European ecological regime. It is expected to reduce risks to forest resource values and to increase ecosystem resilience. However, there remains a significant gap between the broad principles of fire emulation and their operational realization in forest planning. In this paper we will compare three different operational interpretations of fire emulation management with each other and with several more traditional approaches to forest management. To simplify the analysis, we restrict our attention to clearcut timber harvesting as the single management treatment.

We begin with a description of the modelling system and its components. This is followed with an application of the system to the Goldstream watershed in the North Columbia Mountains of British Columbia. Simulated outcomes of alternative forest management strategies are compared and discussed in terms of financial and biodiversity measures.

FOREST MODELLING SYSTEM

The forest modelling system is comprised of a database, a forest management submodel, a forest simulation submodel, a valuation submodel and a fire hazard submodel (Figure 1). Strategic forest management scenarios are represented as a set of alternative operational goals and constraints for the system to evaluate. These are presented as inputs to the tactical forest management submodel. The tactical forest management submodel schedules the application of forest management treatments over the simulated time horizon. The forest database is a spatially referenced set of information on

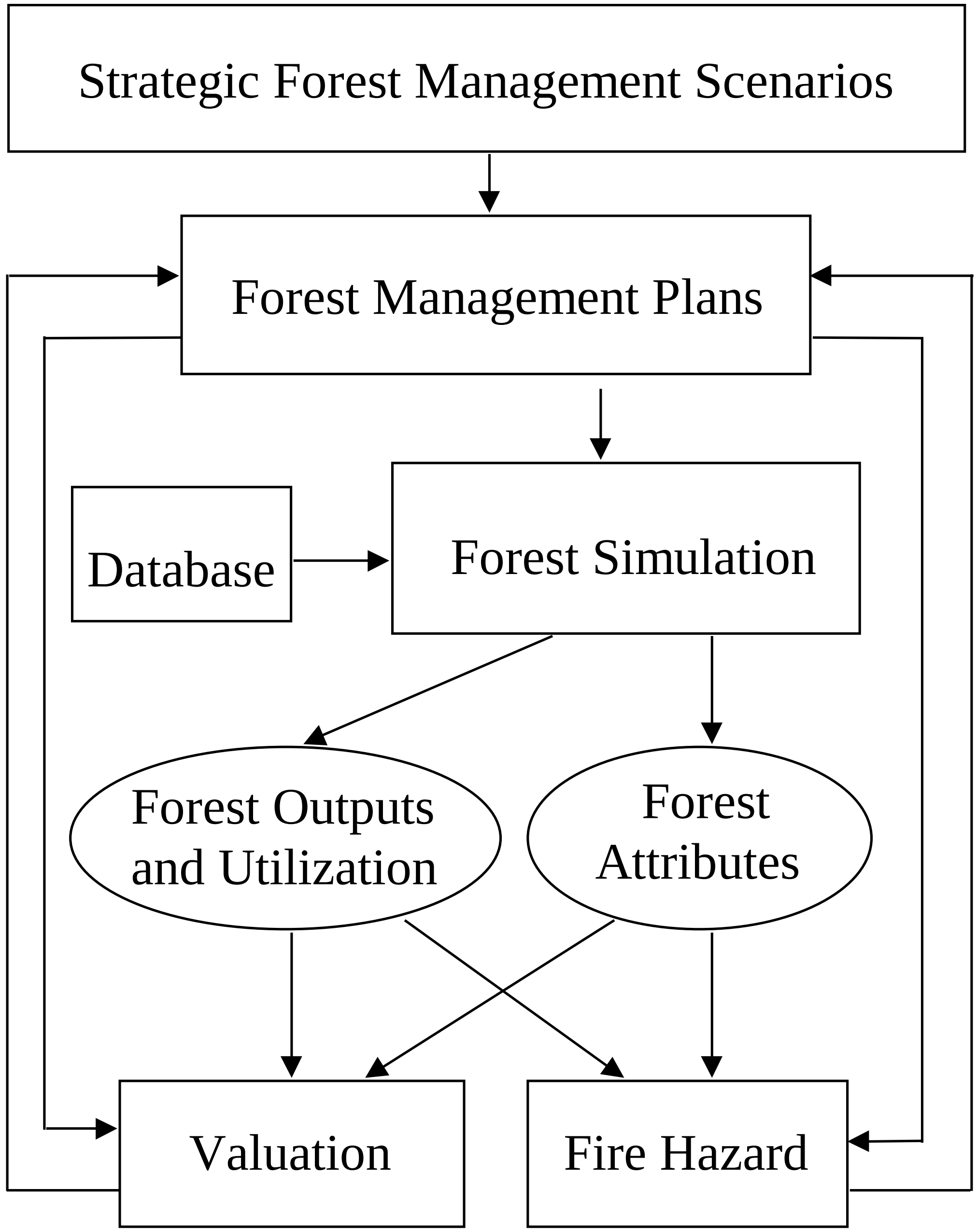

Figure 1. Forest Modelling System

the forest land base and its attributes. The database is managed by a geographic information system (GIS) which can also be used to display outputs for interpretation and evaluation. The forest simulation submodel predicts stand growth, yield and succession over time, given the forest management treatments specified by the tactical management submodel. The valuation submodel calculates financial returns from forest products and services and other, nonfinancial measures of forest values. The fire hazard submodel calculates the fire hazard potential of each stand based upon forest attributes, forest utilization and topography. Results of the forest valuation and fire hazard submodels are used in the forest management submodel to determine the selection of forest management treatments in the ensuing simulated period. The system is modular in design, so that any submodel can be replaced with another which accomplishes the same tasks but uses different procedures or algorithms. For example, the database we developed could be replaced with a similarly structured database for another forest region. The following sections describe the details of the database, the submodels and the set of strategic scenarios that was evaluated.

Database

The study area is the Goldstream watershed, located in the North Columbia mountains of Southeastern British Columbia, just north of Glacier National Parks. This area has significant timber, wildlife and recreation values. The watershed ranges from 500 to 3,700 metres elevation. Its 92,000 hectares include 24,000 hectares of commercially operable forest. The watershed also provides critical winter habitat for woodland caribou, a threatened species which migrate from high elevation summer habitat in the adjacent National Parks to overwinter in the study area, and internationally acclaimed winter recreation opportunities.

One to twenty thousand scale TRIM digital maps were used as a basis for all GIS analysis. Planimetric positions of streams, lakes, wetlands, ice fields and roads were available from this database. MapInfo™ software was used for the project. Sixteen TRIM sheets were required for the Goldstream watershed. The forest resource spatial information was obtained in digital format from the Inventory Branch, B.C. Ministry of Forests (MoF). The data included the digital forest cover positional files at the 1:20000 scale and associated forest inventory attribute files. The forest cover contained information on species characteristics such as dominant species, height, age, crown closure, and site characteristics.

The MoF provided us with a copy of the total chance harvest layout for the area. Cutblocks were identified based on standing timber, site and growing conditions, and harvest guidelines for resource emphasis areas. The cutblock plan included identification of the road network, road construction and maintenance costs, harvesting systems, and harvesting costs for each block. The Goldstream watershed was divided into 3,970 polygons, of which 3,404 blocks covering 24,000 hectares are growing harvestable forest stands. These are the forest stands with positive commercial value which are available for harvest under the MoF's current regulations. The blocks average 7 hectares and range in size from 1 to 17 hectares. The only management option considered in this planning exercise is whether and when to cut each block. The planning horizon was 120 years, a typical rotation for this region, divided into 12 planning periods of ten years each. Harvesting was limited to a single clearcut within one of these planning periods.

A dominant forest type was assigned to each forest polygon based on the Ministry of Forests digital forest cover data. Seven forest types were included: Douglas-fir, western red cedar, western hemlock, true firs, Engelmann spruce, pine, and deciduous forests. Four site qualities were distinguished in the database: good, medium, poor, and low. The median site index for each forest type present in the Goldstream was used as the basis for projecting the growth and yield.

Forest Simulation Submodel

The simulation forecasts the forest development over time, providing an experimental universe in which to test the probable outcomes of management alternatives. The simulation utilizes a set of curves which relate forest stand attributes to stand age. Each curve set contains four curves: merchantable volume, dominant tree height, stand density, and crown closure. Separate curve sets are used for each combination of species and site quality. The curves were generated using the MoF forest stand growth model WinTIPSY version 1.3 (Mitchell et al. 1995). Operational adjustment factors were set so that simulated merchantable yields were equal to those used in the recent timber supply analysis for the Golden Timber Supply Area (B.C. Ministry of Forests 1993). Two site specific adjustments were made to these curves (Vertinsky et al. 1996). For each forest stand a volume correction factor and a height correction factor were computed as the ratios of the inventoried volume to the predicted volume and the inventoried height to the predicted height. Upper and lower bounds of 2.0 and 0.5 were set to the correction factors. At each simulated period the site specific correction factors were multiplied by the volume and height predicted by the standard curve to obtain the site specific stand volume and height. The forest dynamics were modelled for different management scenarios over the 120 year rotation. The results were expressed in terms of the total timber volume harvested and the net present value of the harvest (Thompson et al. 1994).

The forest dynamics model was implemented as an Excel spreadsheet. The state of the forest at each decade starting from the present constituted a separate sheet in the third dimension of the spreadsheet. For each decade, harvested polygons were regenerated to age 5 and the remaining forest polygons were advanced in age by 10 years. Corresponding forest attributes, timber outputs, fire hazard (see below) and forest structural diversity (see below) were calculated from lookup tables and linked spreadsheets. Simulation results were output to the GIS for display and spatial analysis. The timber harvests were also used in a separate spreadsheet for detailed economic calculations (Thompson et al. 1993).

Fire Hazard Submodel

The forest fire hazard model was developed to identify the likelihood of light, moderate or severe fire in forest stands over a single or multiple watershed landscape. It is based conceptually upon the biogeoclimatic[1] and topographic attributes of forest stands which contribute to fire hazard and risk. These include such forest attributes as fuel load, ladder fuels, height to the base of the live crown, snags and species composition. Because many of these factors are not available as part of a standard forest inventory, they were modelled in terms of available data. Thus, the fire model is based upon standard inventory data on forest stand attributes as well as topography, climate, fire prevention actions and other human activities. The model uses these data to provide an assessment of fire risk and hazard. Where sufficient data on fire ignition risk are available, the model can be used to distinguish between risk of ignition events (e.g., lightning strikes, recreation accidents, industrial accidents), the hazard or opportunity for such an event to trigger a fire, and the likelihood that the fire will grow to moderate or catastrophic size. Similar fire hazard models were developed for Bowron Lakes and Mount Robson Provincial Parks (Blackwell et al. 1996a,b) and a more detailed model for the Seymour, Capilano and Coquitlam watersheds near Vancouver (Acres et al. 1997).

The fire hazard model described here bases its predictions on standard vegetation inventory classifications and TRIM topographic data. Thus, it differs from the Canadian Forest Fire Behaviour Prediction (FBP) system, which bases its predictions upon fuel types which do not follow standard

[1] Biogeoclimatic ecosystem classification is a systematic method used in British Columbia to classify terrestrial ecosystems

vegetation inventory classifications. More similar to the model discussed here is the system developed by Tymstra and Ellehoj (1994) for relating land classification from the Alberta Vegetation Inventory (AVI) to FBP fuel types. Their method, using forest land attributes such as moisture regime, crown closure, stand height, species composition, stand structure, non-forest vegetation type, and non-vegetated land for fire behaviour classification, was similar to our use of forest land attributes for fire hazard rating. A similar approach was also taken by Vasconcelos et al. (1994) to modelling fire behaviour in mountain environments.

Our model for the Goldstream was implemented using eight factors: slope, elevation, aspect, biogeoclimatic subzone, successional stage (stand age), species composition, crown closure and area use. As data for fuel load, ladder fuels and height to live crown were not available for the Goldstream, these were estimated from standard forest inventory data using relationships developed in other studies (Acres et al. 1997) and do not appear explicitly in the final model. For each of the model factors, a fire hazard score is computed. These scores are summed to give the total fire hazard score. The totals can range from 10 to 41 on vegetated sites; non-vegetated sites are assigned fire hazard rating = Zero. Other fire hazard ratings are assigned by the total fire hazard score: 10–17 = Low; 18–26 = Medium; 27–33 = High; and 34–41 = Extreme. Details of the fire hazard scores follow.

Slope was taken as the mean percent slope for each polygon. Forest stands on steeper slopes have greater fire hazard. The slope classes and hazard scores are: 0–10%, 2; 10–20%, 3; 20–40%, 4; 40% and greater, 5. Elevation was taken as the mean elevation for each polygon. Lower elevation forests have greater hazard. The elevation classes and hazard scores are: 0–800 m, 5; 800–1000 m, 4; 1000 m and greater, 1. Aspect was taken as the mean aspect for each polygon. Southern exposures have greatest fire hazard. The aspect classes and hazard scores are: 0–110^o, 2; 110–150^o, 4; 150–240^o, 5; 240–300^o, 4; 300–360^o, 2; level (no aspect), 3. The biogeoclimatic subzones in Goldstream are interior cedar hemlock (ICH) and Engelmann spruce/subalpine fir (ESSF). The subzone hazard scores are 4 for ICH sites and 2 for ESSF sites.

Stand structural stage is a measure of forest development. The highest fire risk is in pole/sapling and young forests. The structural stages with typical ages in parentheses and hazard scores are: Non-forested, 1; Shrub/Herb (1–20 y), 2; Pole/sapling forest (20–40 y), 5; Young forest (40–100 y), 5; Mature forest (100–250 y), 4; Old forest (250 y or greater), 3. Relative species

according to their topography, site, soil and vegetation properties (Meidinger and Pojar 1991) composition is both an indicator of site conditions and directly affects flammability of the fuel complex. The lowest fire hazard is associated with deciduous (D) forest stands. Higher fire hazard is associated with western red cedar (Cw) and western hemlock (Hw). The highest fire hazard is associated with Douglas fir (F), true firs and spruce. The vegetation composition and associated hazard scores are: Non-vegetated, 0; $D > 60\%$, 1; $20 < D \leq 60\%$ & $F+Cw+Hw > 40\%$, 3; $D \leq 20\%$ & $Cw+Hw > 40\%$, 4; $D \leq 20\%$ & $Cw+Hw \leq 40\%$, 5. Crown closure provides an indicator of the ease with which fire can spread. Higher crown closure increases fire hazard. The crown closure classes and hazard scores are: 0–35 %, 1; 35–45%, 2; 45–55%, 3; 55–65%, 4; 65% or higher, 5. The final factor, area use, is a measure of the extent to which human activity contributes to increased fire hazard. Activity measures and their hazard scores are: Low – no roads, 1; Moderate – roaded, 4; High – active timber harvesting (or other forest operations), 7.

In a test of the comparable fire hazard model developed for the Vancouver region using an independent database which included the necessary forest and terrain attributes for over 300 polygons, the model correctly classified 65% of Low and Medium hazard polygons and 74% of the High and Extreme hazard polygons.

Forest Valuation Submodel

The valuation models estimate the value of forest products, forest utilization and forest structure and pattern for a given harvest plan. Two measures of forest values were computed: net present value of the timber (NPV) and structural diversity.

Net present value in the absence of fire was computed as the difference in 1997 dollars between gross timber revenues and harvest costs over a time horizon of 120 years (one forest rotation) using a four percent discount rate. Both real log prices and harvest costs were assumed to remain constant over the 120 year time horizon. Gross revenues were computed as the sum over all timber types of log value times log volume. Log value, the price paid for logs at the mill gate, depends on species, log grade and piece size. Average log values for each timber type, that is, species, site class and age class, were estimated from past studies (Nawitka Resource Consultants 1987; Sterling Wood Group 1988; Thompson et al. 1992; Stone et al. 1996) and converted to 1997 dollars assuming no change in real prices..

The harvest costs were divided into five components: road building and maintenance, tree-to-truck, log hauling, silviculture and administration. Each cutblock was assigned to one of three harvest systems: skidding, cable logging or helicopter logging with different harvest costs. Key factors in the harvest system assignment were slope, expected harvest volume, maximum skid distance and site wetness. An average road construction cost of $25,000 per kilometre for the Goldstream was estimated from MoF data (Stone et al. 1996). These costs vary with terrain, being higher for the steeper terrain which requires cable logging ($38,000 per kilometre) and lower for helicopter logging ($15,000 per kilometre). This cost was assigned to each polygon as the incremental cost of access. Tree-to-truck costs are the costs of cutting, delimbing and bucking the trees, bringing the logs to roadside, and loading the logs on trucks. These costs were estimated as $16, $27 and $61 per cubic metre of wood for skidding, cable logging and helicopter logging, respectively (Stone et al. 1996). The cost of hauling the logs to the mill were estimated as $0.10 per kilometre for unpaved roads and $0.09 per kilometre for paved roads (Sterling Wood Group 1988, 1989). An average silviculture cost of $863 per hectare was used (Stone et al. 1996). Road maintenance costs could not be assigned to specific cutblocks owing to inadequate digitization of road data. Therefore, they were included in an average administration cost of $11.00 per cubic metre (for further details log values or harvesting costs, see Brown et al. (1994)). Note that this average does not incorporate the many administrative and planning costs of compliance with the Forest Practices Code (CIT). These were not included due to the paucity and inconsistency of available data.

Differences between management plans result in differences in forest fire hazard, which in turn result in differences in the expected number of forest fires and the area burned. These have several impacts on financial values: (1) direct costs of fire suppression; (2) indirect costs of fire suppression; and (3) lost revenue from timber which is burned rather than harvested. We have modelled these impacts on financial returns in terms of their contribution to the net present value of the timber in the watershed.

Direct costs of fire suppression are roughly proportional to the number of fires and the area burned. Based upon B.C. Ministry of Forest Annual Reports for the past decade, the average annual direct cost of fire suppression in the Nelson District is approximately $2.50 per year per hectare of "current productive and available" forest land. For the 22,518 ha of forest in the Goldstream watershed, this amounts to an annual cost of $57,500. At a 4% real discount rate for the 120 year time horizon considered in this study, the annual stream of costs corresponds to a present cost of 1.5

million dollars. We assumed that the average number of fires and area burned is proportional to the area in the high and extreme fire hazard classes and that the current direct fire suppression costs are appropriate for the Goldstream watershed under a no harvesting scenario. Then we calculate the present value of direct fire suppression costs for a given management scenario as being 1.5 million dollars times the ratio of the average area of high and extreme fire hazard classes under the no harvest scenario to the average area of high and extreme fire hazard classes under the given scenario.

The indirect costs of fire suppression (fire suppression preparedness), which includes fire management, air operations, aircraft availability and administration, bear a more complex relationship to fire occurrence than that of direct fire suppression costs. Indirect costs generally increase following large losses of forest from fires. However, there is little evidence to suggest that these costs decrease significantly over time in the absence of substantial fire losses. As the Goldstream watershed is only about 1% of the area of the Nelson Forest District, we have assumed for the purposes of the present study that fire activity in the watershed will have no impact on District-wide spending. Thus, indirect costs of fire suppression are assumed to be independent of changes to fire hazard in the Goldstream watershed.

The lost revenue from timber which burned depends upon a number of factors, including value of the burnt timber, any salvage value and the value of the remaining available timber. Based upon MOF data on volume losses of mature timber to wildfires, we estimated the loss for the Nelson Region as 0.4% per year of the mature timber volume. We further assumed that this loss is proportionate to the area of forest with high or extreme fire hazard. Over a 120 year time horizon and at a 4% discount rate, the average loss amounts to an present value of $318 per hectare for the 8,959 hectares of high or extreme fire hazard forest in the Goldstream watershed.

The second measure of forest value, structural diversity, is a measure of biodiversity. We used a contagion index (Li and Reynolds 1993; Parresal and McCollum 1997) as a means of quantifying forest patterns across the landscape. Our measure of structural diversity indicates the degree to which adjacent forest stands differ in structural stage. In each planning period each polygon was classified into one of six structural stages: non-vegetated, shrub/herb, pole/sapling, young forest, mature forest or old forest. The vegetated classes correspond to forests with dominant trees of age 0–20, 20–40, 40–100, 100–250 and 250+ years, respectively. Between the 3,970 polygons in the forest management zone there are 7,950 boundaries. We recorded a score of one for each boundary which separated two polygons in different structural stages and of zero for each boundary which separated two polygons in the same structural stage. The structural diversity of the watershed for each period was calculated as the percent of ones; that is, the sum of the scores divided by the number of boundaries times 100. The numeric value of structural diversity can range from 0 to 100%.

Interpretation of the impact of fire emulation on biodiversity and forest structure and pattern depends in part on the choice of measure. The measure defined above is relatively small for a large, homogeneous forest and relatively large for a forest fragmented into a patchwork of small areas of varying successional development. Thus, the biodiversity measure used here correlates positively with some biodiversity measures, but negatively with others. For example, forest ecosystem fragmentation often correlates positively with the biodiversity of exotic animal species but negatively with the biodiversity of indigenous species. While it is generally advisable to measure biodiversity in more than one way (Silbaugh and Betters 1997), other biodiversity measures were not possible with the available data.

Several additional (secondary) measures of harvest schedule performance were calculated: harvest volume (total over the planning horizon), percent of polygons with high or extreme fire hazard (maximum over the 12 planning periods), green-up and adjacency violations (mean annual number over the planning horizon) and harvest unevenness (ratio of largest harvest in any planning period to smallest harvest in any planning period).

Forest Management Submodel

The tactical forest management model provides a means of developing harvest schedules which maximize net present value while meeting even flow, adjacency and other constraints. Changing public attitudes toward forest land use in North America have led to a shift in forest management from the single-use paradigm, usually timber production, to a multiple-use paradigm. A common approach to meeting multiple objectives is to frame the management problem as one of maximizing one of these objectives while incorporating the other objectives in the constraint set. Linear programming methods have been used for over two decades to solve such harvest scheduling problems (e.g., Walker 1976; Johnson and Scheurman 1977; Tedder et al. 1980; Johnson and Stuart 1987; Navon 1990).

Forest management planning in British Columbia requires consideration of numerous restrictions on timber harvesting, including spatial constraints which cannot be handled by linear programming. These constraints restrict the management options on a given tract of forest land on the basis of the status of or activities on an adjacent tract. An example of such 'adjacency' constraints are 'green-up' constraints which forbid the harvest of a block of forest when the forest on any adjacent block is shorter or younger than some specified limit. Adjacency constraints represent a significant technical challenge since they are integer constraints.

PROBLEM FORMULATION

The objective function was defined as a linear combination of four elements: (i) net present value of the timber harvested; (ii) maximum over the planning period of the area in the watershed designated as high or extreme fire hazard; (iii) even-flow of timber harvest; and (iv) nonviolation of adjacency constraints. The choice problem was defined formally as follows:

Let B = the number of timber blocks,
T = the number of periods,
A(b) = the area of block b,
v(b,t) = the volume of timber harvested from block b if cut in period t,
w(b,t) = the NPV of timber harvested from block b if cut in period t,
s(b) = the period in which block b is cut ($s=\infty$ if b is not to be cut).
S = the harvest schedule = {s(b), b=1,...,B}

Then the volume of timber harvested in period t by schedule S is

$$V(t,S) = \Sigma_b\, v(b,s(b)) \text{ for } \{b:s(b)=t\} \qquad [1]$$

Similarly, the NPV of timber harvested in period t by schedule *S* is

$$W(t,S) = \Sigma_b\, w(b,s(b)) \text{ for } \{b:s(b)=t\} \qquad [2]$$

For a given schedule *S*, the NPV, W(S), is found by summing W(t,S) over t.

$$W(S) = \Sigma_t\, W(t,S) \qquad [3]$$

Let f(b,t,i) be the fire hazard in period i for block b if cut in period t. Define F(b,t,i) as

$$F(b,t,i) = A(b) \text{ if } f(b,t,i) = \text{high or extreme}, \qquad [4]$$

$$= 0 \qquad \text{otherwise.}$$

Then for a given schedule *S*, the high and extreme fire hazard area in period i is

$$F(S,i) = \Sigma_b\, F(b,s(b),i) \qquad [5]$$

and the overall fire hazard measure is the maximum over the planning horizon,

$$F(S) = \text{Max}_i\, [F(S,i)] \qquad [6]$$

Our measure of intertemporal evenness of timber harvest was

$$E(S) = Max_t [V(t,S)] - Min_t [V(t,S)] \quad [7]$$

Let J(b) = the set of blocks adjacent to block b,

g(b) = the number of periods for block b to green-up (2 periods for all blocks in the present application),

G(b,t) = the set of all possible adjacency violations if block b were cut in period t.

So,

$$G(b,t) = \{(b',t'): b'' \varepsilon J(b), \bullet t'-t \bullet < g(b')\} \quad [8]$$

Let N[G] = the number of elements in set G.

Then the number of adjacency violations in schedule *S* is

$$M(S) = N[U_b(G(b,s(b)))]/2 \quad [9]$$

For positive constants α, ß, τ and δ, the objective was:

$$Max_S [\alpha W(S) - ßF(S) - \tau E(S) - \delta M(S)]. \quad [10]$$

Solution Method

A variety of methods have been attempted to provide practical solution methods for the harvest scheduling problem with spatial constraints. These include mixed integer programming (Kirby et al. 1980), random search (O'Hara et al. 1989; Clements et al. 1990; Nelson and Howard 1991), Monte Carlo integer programming (Nelson et al. 1991; Daust and Nelson 1993; Jamnick and Walters 1993), Lagrangian relaxation (Hoganson and Rose 1984), heuristics combined with relaxation methods (Gross and Dykstra 1988; Meneghin et al. 1988; Torres and Brodie 1990), multiple-criteria decision algorithms (Howard 1991; Howard and Nelson 1993), stable set theory (Barahona et al. 1992), fuzzy control (Bare and Mendoza 1992) and simulated annealing (Lockwood and Moore 1993). Tabu search has proved to be an effective heuristic technique for solving combinatorial problems (Glover and Laguna 1993). The tabu search method is a local search heuristic which progresses from a solution to a neighbouring solution subject to some 'tabu' restrictions. We have incorporated in our model an algorithm developed by Brumelle et al. (1998) which utilizes the tabu search technique. The algorithm was modified to incorporate fire hazard minimization.

Strategic Forest Management Scenarios

Our objective in the choice of scenarios was to evaluate alternative interpretation of the fire accommodation and emulation paradigm and to compare these to more traditional strategies of harvesting. Three harvest schedules were developed under the fire emulation paradigm. The first involved scheduling timber harvesting to mimic a natural disturbance regime, without regard to regulatory practices or forest resource values. The second and third attempted to achieve a time course of desired forest structure and pattern, with explicit consideration of forest resource values. Five other harvest schedules were chosen to provide comparisons. Four of them were defined by all the combinations of two common regulatory regimes, green-up and adjacency regulation and even flow regulation. The final schedule was no harvest. All the harvest schedules were defined over a one hundred twenty year time horizon, divided into twelve periods of ten years. Each block could be harvested during one of those periods or could remain unharvested. To implement the first two scenarios, we replaced the management submodel with prespecified harvest plans to emulate alternative fire regimes. The other scenarios were generated by manipulating the weights placed on the different management objectives.

The fire accommodation and emulation strategies used fire hazard measures to guide harvesting. The first schedule (F1) was an attempt to mimic fire as a stand replacing disturbance across the entire landscape. This approach attempts to closely mimic the effects of fire while retaining timber values. We assumed that a catastrophic fire would destroy all stands with high and extremely high fire hazard rating. Consequently, in this scenario all blocks with fire hazard ratings of high and extreme were harvested in the first planning period. In subsequent periods, each of the remaining blocks was harvested in the period which maximized its net present value.

The second schedule (F2) was an attempt to reduce the fire hazard for the watershed as a whole by systematically harvesting blocks with higher fire hazard earlier. This approach to hazard reduction attempted to mimic a series of less catastrophic fires. While it focused on rapid fire hazard reduction, it ignored the effects of forest succession on future forest fire hazard. Blocks with fire hazard indices of 80 and higher were harvested in the first decade. In the second period block with fire hazard indices 76–79 were harvested. In periods 3 to 11 blocks with fire hazard indices 72–75, 68–71, ..., 40–43 were harvested, and in the final period the remaining blocks with fire hazard indices 39 or less were harvested.

The third schedule (F3) was an attempt to minimize fire hazard within the watershed throughout the planning period while harvesting every block. This approach of long term fire hazard minimization aimed at maintenance of forest resilience. The tabu search algorithm was used with the objective of maximizing the net present value of the cumulative harvest while meeting a constraint on the maximum area with high or extreme fire hazard. The fire hazard constraint was initially set to a large value and was reduced systematically on successive applications of the search algorithm until no improvement in minimizing fire hazard was achieved.

The simulated results of following these schedules are compared with those of five other schedules which ignore fire considerations.

The fourth schedule (UNREG) was an unregulated plan which maximized the net present value of each timber stand. Each block was scheduled to be cut during the period which maximized its net present value. This schedule was included to identify an upper bound on potential financial return. It was expected also to provide an indication of extreme, generally worst, results for other forest values.

The fifth schedule (G&A) imposed a green-up and adjacency restriction to the harvest. No block was cut within 20 years of an adjacent block. The tabu search algorithm was used to maximize the net present value of the harvest under this constraint.

The sixth schedule (EVEN) imposed an even flow restriction on the harvest. The tabu search algorithm was used to maximize the net present value of the harvest while minimizing the difference in timber volume cut between planning periods. Relative weights of these two objectives were adjusted until the difference between the largest and smallest harvest volumes over the ten-year planning periods was 30% or less.

The seventh schedule (EVEN/G&A) imposed both the green-up and adjacency constraints and the even flow constraint. The tabu search algorithm was used to develop a harvest schedule which met the restrictions of both schedules EVEN and G&A.

The eight schedule (NOCUT) was a no harvest schedule. This was included to provide a measure of non-timber values under the least intrusive management.

RESULTS

The three fire emulation and hazard reductions schedules (F1, F2 and F3) gave quite different results in terms of the evaluation criteria (Table 1). Emulation of a catastrophic fire (F1) was very similar to the unregulated schedule (UNREG). They had the highest NPV and the lowest structural diversity of the eight schedules. Compared to those two, fire hazard reduction through emulation of a series of smaller fires (F2) and fire hazard minimization (F3) yielded about one quarter the NPV but had double the structural diversity. Surprisingly, emulation of a series of smaller fires (F2) gave only a modest reduction in fire hazard over that of the catastrophic fire emulation (F1) or the unregulated schedule (UNREG). However, fire hazard minimization (F3) resulted in a much lower fire hazard, exceeded only by the no harvest option (NOCUT).

Table 1. Harvest schedule results.

Schedule	Primary Measures		Secondary Measures			
	NPV $ '000,000	Structural Diversity	Harvest Volume '000 m^3	Fire Hazard '000 ha H & Ex	G & A violations #/yr	Harvest unevenness[1]
F1	347	18	147	15.1	42	1061%
F2	93	34	154	14.1	31	258%
F3	95	37	159	9.6	27	273%
UNREG	347	16	151	14.6	36	928%
G&A	216	53	150	12.7	0	416%
EVEN	148	32	159	10.7	28	2%
EVEN/G&A	95	58	152	10.8	0	32%
NOCUT	–4	22	0	9.0	0	0%

[1] ratio of largest harvest in any decade to smallest harvest in any decade

Schedule which deferred harvest of many areas to a later period than that specified in the unregulated schedule had a correspondingly lower NPV. Compared to the unregulated schedule (UNREG), imposing green-up and adjacency limits (G&A) resulted in about a one third reduction in NPV, imposing an even flow restriction (EVEN) reduced the NPV by about 60%, and the combination of the two restrictions (EVEN/G&A) reduced the NPV by about 75%. This later reduction in NPV was about the same as that which resulted from the two fire hazard reduction scenarios (F2 and F3), while the no harvest option (NOCUT) had a negative NPV as it generated no revenues but included fire suppression costs.

Enforcement of green-up and adjacency restrictions (G&A and EVEN/G&A) provided the highest levels of forest structural stage diversity. In part this occurred because the measure of diversity was based upon structural stage differences between adjacent blocks. Thus, requiring an age difference between blocks subsequent to their harvest necessarily promoted structural diversity. A longer period of restriction (say 30 or 40 years rather than 20) would further enhance this measure of diversity. The two schedules which aimed to reduce fire hazard (F2 and F3) and the even flow schedule (EVEN) also performed fairly well in terms of diversity, while the no harvest option (NOCUT) performed poorly. The successional tendency toward large areas of even-aged forest created by occasional catastrophic disturbance promotes a low degree of structural diversity. In contrast, frequent smaller disturbances, whether natural or artificial, promote a higher degree of structural diversity.

Fire hazard was lowest for the unharvested forest (NOCUT). It was nearly as low for the schedule which minimized fire hazard while harvesting all the blocks of timber (F3). The catastrophic fire emulation (F1) and unregulated (UNREG) harvest schedules led to the highest levels of fire hazard, followed closely by the fire hazard levels resulting from the immediate fire hazard reduction schedule (F2). This last observation is important in highlighting the challenge of scheduling timber harvesting without significantly increasing fire hazard.

The two regulatory goals, even flow and green-up and adjacency, were achieved only when they were set as strict constraints. In the absence of these constraints, the long term fire hazard minimization schedule (F3) had the best combined performance on those two criteria.

DISCUSSION AND CONCLUSIONS

As demonstrated above, different interpretations of the fire emulation paradigm may result in a wide range of impacts on forest values. The first harvest schedule examined (catastrophic fire emulation, F1) attempted to simulate the natural disturbance regime by mimicking an extensive stand replacing fire. Such an approach may be seen as "natural" in that it creates the same sort of landscape as a naturally occurring severe fire. However, the resulting landscape is very similar to that created by an unregulated timber harvest which maximizes financial returns. It is not surprising that this interpretation of the fire accommodation and emulation paradigm was received enthusiastically by many firms as ecological and economic objectives coincide.

The second and third harvest schedules (emulation of a series of smaller fires, F2, and fire hazard minimization, F3) attempted to reduce the risk of an extensive fire by cutting high hazard stands. This approach of managing the landscape to reduce the risk of extreme events has a similar philosophic basis to many other human endeavours in which "nature is tamed." Preferred states of the natural system are identified, and management actions are taken to create and maintain those states. In the present example, this "taming of nature" is traded-off with a timber production objective. The two harvest schedules differ in the technical details of how they attempt to maintain a lower fire hazard. While they produce nearly equal results in terms of the economic and biodiversity objectives, fire hazard minimization (F3), which incorporates a feed-forward control strategy, was much more successful than emulation of a series of smaller fires (F2) in reducing fire hazard.

None of the fire emulation schedules took account of regulatory practices or forest resource values. A comparison with the five more traditional harvesting regimes showed that regulatory harvest restrictions such as even flow and green-up and adjacency provided better fire hazard reduction than emulation of either a catastrophic fire or a series of smaller fires (F1 or F2). This serendipitous result indicates that a blend of the fire emulation management paradigm with more traditional forest management approaches may have merit.

In future studies we will explore combining fire emulation with traditional forest management. The forest modelling system will be used to achieve a time course of desired forest structure and pattern while explicitly considering forest values and harvesting constraints. The studies will be broadened to consider the impact of forest management on wildlife and recreation in addition to timber and biodiversity values and will examine the necessity of relaxing strict regulatory limits on cutblock size and green-up and adjacency periods in order for harvesting to produce a forest landscape consistent with the natural disturbance regime.

CITATIONS

Acres International, B.A. Blackwell & Assoc., J.M. Ryder & Assoc., Northwest Hydraulic Consultants, Oikos Ecological Services, Phero Tech and Timberline Forest Inventory Consultants (1997). GVRD Watershed Ecological Inventory Program. Methodolgy Report. Contract Report. Greater Vancouver Regional District, Burnaby, B.C.

Barahona, F., A. Weintraub and R. Epstein (1992). Habitat dispersion in forest planning and the stable set problem. *Operations Research* 40: S14–S21.

Bare, B.C. and G.A. Mendoza (1992). Timber harvest scheduling in a fuzzy decision environment. *Canadian Journal of Forest Research* 22: 423–428.

Blackwell, B.A. & Associates Ltd., Keystone Wildlife Research, Laing and McCulloch Forest Mangement Services Ltd., Oikos Ecological Services Ltd. and Phero Tech Inc. (1996a). Bowron Lakes Provincial Park Vegetation Management Plan. Volumes 1 & 2. Contract Report, B.C. Ministry of Environment, Lands and Parks, Victoria.

Blackwell, B.A. & Associates Ltd., Keystone Wildlife Research, Laing and McCulloch Forest Mangement Services Ltd., Oikos Ecological Services Ltd. and Phero Tech Inc. (1996b). Mount Robson Provincial Park Ecosystem Management Plan. Volumes 1 & 2. Contract Report, B.C. Ministry of Environment, Lands and Parks, Victoria.

Boychuk, D. and D. L. Martell (1996). A multistage stochastic programming model for sustainable forest-level timber supply under risk of fire. *Forest Science* 42: 10–26.

B.C. Ministry of Forests (1993). Golden TSA timber supply analysis. Integrated Resource Branch, B.C. Ministry of Forests, Victoria, 60 pp.

Brown, S., H. Schreier, W.A. Thompson and I. Vertinsky (1994). A decision support system incorporating geographic information to resolve forestry/wildlife conflicts. *Journal of Environmental Management* 42: 349–364.

Brumelle, S., W.T. Stanbury, W.A. Thompson, I. Vertinsky and D. Wehrung. (1990). Framework for the analysis of risks in forest management and silvicultural investments. *Forest Ecology and Management* 35: 279–299.

Brumelle, S., D. Granot, M. Halme and I. Vertinsky (1997). A tabu search algorithm for finding good forest harvest schedules satisfying green-up constraints. *European Journal of Operational Reserach*. (in press).

Christiansen, N.L., J.K. Agee, P.F. Brussard, J. Hughes, D.H. Knight, G.W. Minshall, J.M. Peek, S.J. Pyne, F.J. Swanson, J.W. Thomas;, S. Wells, S.E. Williams and H.A. Wright (1989). Interpreting the Yellowstone fires of 1988: ecosystem responses and management implications. *Bioscience* 39: 678–685.

Clark, W.C. (1980). Witches, floods, and wonder drugs: Historical perspectives in risk assessment. pp. 287–318 in R.C. Schwing and W.A. Albers, Jr. (eds.), *Societal Risk Assessment: How Safe is Safe Enough* Plenum Press, New York.

Clements, S.E., P.L. Dallein and M.S. Jamnick (1990). An operational spatially constrained harvest scheduling model. *Canadian Journal of Forest Research* 20: 1438–1447.

Daust, D.K. and J.D. Nelson (1993). Spatial reduction factors for strata-based harvest schedules. *Forest Science* 39: 152–165.

Foster, D.R. (1982). The history and pattern of fire in the boreal forest of southeastern Labrador. *Canadian Journal of Botany* 61: 2459–2471.

Glover, F. and M. Laguna (1993). Tabu search. Chapter 3, pp. 70–150 in C.R. Reeves (ed.), *Modern Heuristic Techniques for Combinatorial Problems,* Blackwell, London.

Gross, T.E. and D.O. Dykstra (1988). Harvest scheduling with nonadjacency constraints. pp. 310–315 in *Proceedings of the Society of American Foresters National Convention*, Rochester, NY.

Heinselman, M.L. (1973). Fire in the virgin forest of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research* 3: 329–382.

Hof, J. (1993). Coactive Forest Management. Academic Press. New York. 189 pp.

Hoganson, H.M. and D.W. Rose (1984). A simulation approach for optimal timber management scheduling. *Forest Science* 30: 220–238.

Holling, C.S. (1981). Forest insects, forest fires and resilience. pp. 445–464 in H. Mooney, J.M. Bommicksen, N.L. Chjristensen, J.T. Lotan and W.A. Reiness (eds.), *Fire Regimes and Ecosystem Properties,* USDA Forest Service, Washington D.C., Gen. Tech. Rpt. WO–26.

Holling, C.S. (1984). Resilience of ecosystems, local surprise and global change. pp. 228–269 in T.F. Malone and J.G. Roeder (eds.), *Global Change*, Cambridge University Press, London.

Howard, A.F. (1991). A critical look at multiple criteria decision making techniques with reference to forestry applications. *Canadian Journal of Forest Research* 21: 1649–1659.

Howard, A.F. and J.D. Nelson (1993). Area-based harvest scheduling and allocation of forest land using methods for multiple-criteria decision making. *Canadian Journal of Forest Research* 23: 151–158.

Jamnick, M.S. and K.R. Walters (1993). Spatial and temporal allocation of stratum-based harvest schedules. *Canadian Journal of Forest Research* 23: 402–413.

Johnson, K.N. and H.L. Scheurman (1977). Techniques for prescribing optimal timber harvest and investment under different objectives – discussion and synthesis. *Forest Science Monograph* 18. 31 pp.

Johnson, K.N. and T.W. Stuart (1987). FORPLAN Version 2: Mathematical Programmer's Guide, USDA Forest Service, Washington, D.C. 158 pp.

Kilgore, B.M. (1973). The ecological role of fire in Sierran conifer forests: its application to National Park management. *Quaternary Research* 3: 496–513.

Kirby, M.W., P. Wong, W.A. Hager and M.E. Huddleston (1980). A Guide to the Integrated Resources Planning Model, USDA Forest Service, Berkeley, CA. 211 pp.

Li, H. and J.F. Reynolds (1993). A new contagion index to quantify patterns of landscapes. *Landscape Ecology* 8: 155–162.

Lockwood, C. and T. Moore (1993). Harvest scheduling with spatial constraints: A simulated annealing approach. *Canadian Journal of Forest Research* 23: 468–478.

MacLean, D.A. and K.B. Porter (1994). Development of a decision support system for spruce budworm and forest management planning in Canada. pp. 863–872 in *GIS 94*, Symposium Proceedings. Vol. 2.

Meidinger, D.V. and J. Pojar (eds.). (1991). Ecosystems of British Columbia. Special Report Series # 6. B.C. Ministry of Forests, Victoria.

Meneghin, B.J., M.W. Kirby and J.G. Jones (1988). An algorithm for writing adjacency constraints efficiently in linear programming models. pp. 46–53 in *The 1988 Symposium on Systems Analysis in Forest Resources*. USDA Forest Service General Technical Report RM–161, Fort Collins, CO.

Mitchell, K.J., S.E. Grout, and R.N. MacDonald (1995). WinTIPSY: User's guide for producing managed stand yield tables with WinTIPST version 1.3 under Microsoft Windows. B.C. Ministry of Forests, Victoria.

Navon, D.I. (1990). Roading Timber RAMM Users Manual. PSW Forest and Range Experiment Station, Berkeley, CA. 44 pp. + appendices.

Nawitka Resource Consultants Inc. (1987). Impact of Intensive Forestry Practices on Net Stand Values in British Columbia. FRDA Report 014. Forestry Canada, Victoria.

Nelson, J.D. and S.T. Finn (1991). The influence of cut-block size and adjacency rules on harvest levels and road networks. *Canadian Journal of Forest Research* 21: 595–600.

Nelson, J.D., J.D. Brodie and J. Sessions (1991). Integrating short-term, area-based logging plans with long-term harvest schedules. *Forest Science* 37: 101–122.

Nelson, J.D. and A.F. Howard (1991). A three-stage heuristic procedure for allocating spatially and temporally feasible cutting rights on public lands. *Canadian Journal of Forest Research* 21: 762–768.

O'Hara, A.J., B.H. Faaland and B.B. Bare (1989). Spatially constrained timber harvest scheduling. *Canadian Journal of Forest Research* 19: 715–724.

Parresal, B.R. and J. McCollum (1997). Characterizing and comparing landscape diversity using GIS and a contagion index. *J. Sustainable Forestry* 5: 249–261.

Pyne, S. (1990). Fire conservancy: The origins of wildland fire protection in British India, America, and Australia. pp. 319–336 in J.G. Goldammer (ed.), *Fire in the Tropical Biota*, Springer-Verlag, Berlin.

Silbaugh, J.M. and D.R. Betters (1997). Biodiversity values and measures applied to forest management. *J. Sustainable Forestry* 5: 235–248.

Sterling Wood Group Inc. (1988). Analysis of Changes in Timber Values due to Silvicultural Treatments Under the Canada-British Columbia Forest Resource Development Agreement. FRDA Report 041. Forestry Canada, Victoria.

Sterling Wood Group Inc. (1989). Expected Delivered Wood Costs for Areas Treated Under the Canada-British Columbia Forest Resource Development Agreement. FRDA Report 079. Forestry Canada, Victoria.

Stocks, B.J. and W.S.W. Trollope (1993). Fire Management: Principles and options in the forested and savanna regions of the world. pp. 315–326 in P.J. Crutzen and J.G. Goldammer (eds.), *Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires*. John Wiley & Sons, New York.

Stone, M., S. Grout and C. Watmough (1996). The TIPSY economist: An economic analysis module for WinTIPSY. B.C. Ministry of Forests, Victoria.

Swedish National Board of Forestry (1990). A Richer Forest. (J. Persson and S. Manu, eds.). The Swedish National Board of Forestry, Jonkoping. 133 p.

Tedder, P.L., J.S. Schmidt and J. Gourley (1980). TREES: Timber Resources Economic Estimation System, Vol. 1, A User's Guide for Forest Management and Harvesting Scheduling. Forest Research Lab Research Paper 31a, Corvallis, OR. 88 pp.

Thompson, W.A., C.S. Holling, D. Kira, C.C. Huang and I. Vertinsky (1979). Evaluation of alternative forest system management policies: The case of the spruce budworm in New Brunswick. *J. Envir. Econ. Manage.* 6: 51–68.

Thompson, W.A., P.H. Pearse, G.C. van Kooten and I. Vertinsky (1992). Rehabilitating the backlog of un-stocked forest lands in British Columbia: A preliminary analysis of alternative strategies. pp. 99 – 103 in P.N. Nemetz (ed.), *Emerging Issues in Forest Policy.* UBC Press, Vancouver.

Thompson, W.A., G.C. van Kooten, I. Vertinsky, S. Brown and H. Schreier (1993). A preliminary economic model for evaluation of forest management in a geo-referenced framework. pp. 208–220 in *Proceedings of the 7th Annual Symposium on Geographic Information systems in Forestry, Environment and Natural Resources Management.* Vancouver, B.C., Vol. 1.

Thompson, W.A., S. Brown, L. Cooper, I. Vertinsky and H. Schreier (1994). A decision support system for evaluating forestry-wildlife-recreation conflicts in the transboundary area of two national parks. pp. 615–624 in *Proceedings of the 8th Annual Symposium on Geographic Information Systems in Forestry, Environment and Natural Resources Management*, February 21–24, 1994, Vancouver, B.C. Vol. 2.

Torres, J.M. and J.D. Brodie (1990). Adjacency constraints in harvest scheduling: An aggregation heuristic. *Canadian Journal of Forest Research* 20: 978–986.

Tymstra, C. and E.E. Ellohoj (1994). Fire behaviour prediction fuel type mapping using the Alberta Vegetation Inventory. pp. 887–893 in *GIS 94*, Symposium Proceedings. Vol. 2.

Vasconcelos, M.J., J.M.C. Pereira and B.P.Zeigler (1994). Simulation of fire growth in mountain environments. pp. 167–185 in M.F. Price and D.I. Heywood (eds.), *Mountain environments and Geographic Information Systems*, Taylor and Francis, London.

Vertinsky, I., W.A. Thompson and H. Schreier (1996). Incorporating variability in modelling forest-wildlife conflicts, using a GIS and multiple account framework. pp 25–27 in *Proceedings of Sustainable Forestry Partnerships: Forging a Network of Excellence.* Edmonton, Alberta, 6–8 March 1996.

Walker, J.L. (1976). Systems Analysis and Forest Resource Management. Society of American Foresters, Washington, D.C. pp. 172–188.

Whelan, R.J. (1995). *The Ecology of Fire*. Cambridge University Press: Cambridge. 346 pp.