Determining Harvest Schedules and Profitability Under the Risk of Fire Disturbance

By

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Abstract

This thesis demonstrates a method of determining harvest schedules based on the uncertainty of natural disturbance, and explores the interactions between disturbances and harvest scheduling. A model of wildfire occurrence is first developed, and the effects of wildfire on forest growth, landscape attributes, and harvesting are evaluated. A method to determine an appropriate harvest target is developed that considers the risk tolerance of the forest owner. The impacts of various model assumptions on estimates of sustainable timber supply are then examined through sensitivity analyses. The impacts on timber supply when natural disturbance is explicitly simulated are more complex than simple reductions to the total amount cut and may be of interest to forest managers who wish to predict the long-term supply profile. A 'buffer' that ensures a sustainable harvest in the face of disturbance is demonstrated in terms of reduced harvest volumes and excess available timber. Sustainable harvest flows within this model are sensitive to both risk tolerance and the time span considered. Assumptions on the ability to salvage disturbed areas and the effects of disturbance suppression further complicate our choice of harvest target, and our lack of ability to constrain the largest disturbances over time may reduce harvest rates, as well as increasing the range of variation in landscape attributes. Estimates of profit from changing rates of forest harvesting provide a measure of the cost of natural disturbance, and when wildfires are suppressed, profit provides a measure of the value of suppression. On a 288,000-hectare area in northeastern BC, the cost of historical natural disturbance was estimated at $4 million per year. Suppressing 98.3% of disturbance events had a value of $1.8 million per year and increased the value of the forest by 50%. Increasing risk tolerance produced higher short-term profits on this landscape, though as buffers are drawn down over the long-term, profits increased very little, and were accompanied by periods with much lower profits.

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Acknowledgements

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1.0 Introduction

Forest fires are known best for their immediate consequences. Individual fires can create drastic changes to stand-level conditions by killing trees and other vegetation, as well as creating conditions that allow new vegetation to re-establish. Where economic values are present in individual stands, fires can reduce or eliminate them, as well as causing damage to private property.

Forest fires are a natural occurrence and are the dominant form of natural disturbance in the boreal and sub-boreal forests of northeastern British Columbia. While many of the impacts of forest fires are easily understood, the long-term impacts of fires on our ability to sustain flows of commercial products and non-timber values from forests are more difficult to estimate. Since fires are unpredictable, our estimates of sustainability and future forest conditions also contain uncertainty. This thesis will attempt to answer some of the questions related to the uncertainty and risk created by fire disturbance, using a spatially explicit forest model.

This is a timely subject given the recent fires in western Canada that have captured public attention. In British Columbia, forest fires burn an average of 25,000 hectares per year, and we currently spend an average of $56 million per year suppressing fires (BCMOF 2003). In some years these costs and the area burned can be much higher. In 2003, an estimated $365 million was spent suppressing fires that burned over 263,000 hectares and destroyed private homes and businesses in adjacent communities (Taudin-Chabot 2003). While the need to protect communities and ensure public safety through fire suppression is obvious, the returns on our investments in forest fire suppression are difficult to quantify. By estimating the cash returns from harvesting under a variety of disturbance and suppression assumptions, this thesis will also attempt to estimate the value of suppressing forest fires, based on changing returns from timber harvesting. With many competing demands on our public sector resources, understanding the value we receive through investments in suppression is essential.

This chapter will outline the background for considering natural disturbance in forest planning and the objectives of the thesis. The issue of uncertainty is introduced, and the uncertainty created by forest fires is described. Methods used to quantify natural disturbance are explained, and some recent examples and results of natural disturbance studies in northern forests are presented. The most recent attempts to integrate natural disturbance into forest models are reviewed, along with questions and issues requiring further research. Finally, the specific research objectives for this thesis are stated in detail.

1.1 Uncertainty and Natural Disturbance

There are many types of uncertainty in forest modelling. Yield from individual stands can be different than predictions from stand-level growth models due to changing soil or climate conditions, fire, diseases or other biological factors (Kimmins 1990). In addition, the data on which models are based are subject to sampling or measurement errors (Weintraub and Abramovich 1995). At a landscape level all of these factors, along with social, economic and policy changes, can create uncertainty in our modelling predictions (Kimmins and Sollins 1989). In British Columbia, natural disturbance uncertainty is generally incorporated into timber supply forecasts by subtracting a percentage from the projected harvest to account for 'non-recoverable losses' (Olivotto 1999, Marshall 1985). Because of the increasingly complex way in which forests are being managed, the use of spatially explicit models is often seen as necessary to provide adequate projections of future forest conditions (Nelson 2000, Bettinger and Sessions 2003). Unless disturbance is accounted for in these models, timber supply projections can be over-estimated (Boyland 2002), and simply applying a correction factor to the projected harvest does not adequately address other values such as landscape pattern and biodiversity.

Natural disturbance in northern forests is dominated by fire. Fire plays a natural ecological role in forests, and has an important influence on the structure and function of ecosystems (Frelich 2002, Weber and Stocks 1998, Kimmins 1987). Lightning and humans are the most significant causes of forest fires in Canada, and although lightning is the cause of only 35% of fires, lightning caused fires account for 85% of total area burned (Stocks 1991).

Forest fires are usually classified by the portion of stand structure affected: ground fires, surface fires, or crown fires can occur on their own or in various combinations (Kimmins 1987). Fire intensity refers to the rate of energy released by a fire. Fire severity refers to the resulting mortality to trees or plants, which is a function of stand conditions and intensity. High intensity crown fires generally kill trees of all sizes. The conditions necessary to support a fire include a mixture of fine and large diameter fuels. Since fires do not generally consume all large fuels, the period of time required to recreate fire conducive conditions can be as little as three to five years (Frelich 2002). Active crown fires are typical in the boreal forest, and complete tree mortality is common (Johnson 1992). During periods of severe drought, crown fires in northern conifer forests become frequent, are often beyond human control, and can account for the majority of area burned (Johnson et al. 1995, Frelich 2002).

1.2 Characterizing Natural Disturbance

A disturbance regime is defined by the frequency, severity and size of disturbance (Frelich 2002). For fire-dominated systems this is often referred to as the fire regime. Johnson and Gutsell (1994) give an overview of the terminology used to characterize disturbance regimes with respect to fire-dominated systems. Survivorship curves describe the cumulative proportion of the landscape surviving longer than a specified time. The fire interval is the probability distribution of the interval between fires at a given location. Depending on the shape of these curves, fire regimes can be classified as fitting into a Weibull or a negative exponential model. With the Weibull model, the probability of a stand burning increases with age. The negative exponential model is really a specific case of a Weibull model, where the hazard of burning is constant with stand age. Other useful ways of describing fire regimes include estimates of fire frequency, which is the probability of a fire in a given location per unit time, and the annual percent burn, which is the proportion of area that burns per year. The fire cycle is the time required to burn an area equal to the study area, though not necessarily every location, as some fire events may overlap, leaving some areas undisturbed during a single fire cycle.

In the case of the negative exponential model, the fire cycle is the same as the fire return interval, and if unchanged through time, it will be reflected in the average age of the forest. The annual percent burn is the inverse of this, which in the case of the negative exponential model, is the same as the fire frequency (Fall 1998). For example, a forest with a fire cycle of 100 years would have an annual percent burn of 1/100 or 1%.

Characterizations such as these can be obtained by examining fire history records. In the absence of historical records, the age-class structure of a forest can be used to derive disturbance regime characteristics, when it can be assumed that fires are stand-replacing. Where fires operate on a stand-maintaining basis, field surveys that examine past evidence of disturbance, such as fire scars, are used to determine disturbance frequency (Fall 1998).

1.3 Disturbance Regimes in Northern Forests

The Forest Practices Code Biodiversity Guidebook (BCMOF 1995) classifies disturbance regimes based on the biogeoclimatic ecosystem classifications (BEC) used in British Columbia. The various BEC classes are grouped into five Natural Disturbance Types (NDTs) with shared disturbance characteristics, and average return intervals are estimated for each regime. Based on this system, northern forests are categorized with several of the five disturbance regimes included in the Biodiversity Guidebook.

Andison (1996) created a characterization of historical disturbance regimes near Prince George. An average disturbance interval of 80 to 100 years was calculated, and the tendency to burn was found to be partially related to stand age, because of an absence of very old stands. This may be due to an increased risk of fire in old stands, or other disturbance agents, or could simply be caused by stands breaking up with age due to other natural causes. However, the vast majority of the landscape patterns were created by a small number of very large fires, which appeared to be age-independent. These infrequent disturbances create a landscape that does not have an equilibrium age-class structure.

Armstrong (1999) reached similar conclusions when he examined fire history records over a large area of forest in northern Alberta, and characterized the rate of disturbance using a lognormal distribution. He then applied this distribution to simulations using a hypothetical forest containing 100 stands, and demonstrated that no equilibrium age- class structure could be identified.

Delong (1998, 2002) characterized historical disturbance occurrence for areas near Prince George by spatially classifying disturbance regimes throughout the region. Forest cover data were used to assess the rate of stand-replacing disturbance based on amalgamated age-class polygons for stands 60 to 80 years old. These stands were assumed to best represent pre-suppression disturbance rates, and to be young enough to minimize bias from re-burning. Estimates of the natural range of variation of landscape conditions for each of the regimes were also produced.

Regimes are also characterized by the size of disturbances. Disturbance patch sizes have been characterized in fire studies by percentages within specific size classes, or using continuous distributions. For example, Stocks (1991) reported that the patch size distribution of fires in north-west Ontario is different depending on fire management. With fire suppression, the distribution follows an exponential distribution that favors smaller fires. Where no suppression occurs, the distribution approaches a normal distribution, with larger fires being common. Cumming (2001b) characterized the fire size distribution for an area of boreal forest in northern Alberta. The logarithm of fire size was found to be exponentially distributed, although fires had a maximum size of approximately 650,000 hectares, which requires the distribution to be truncated. DeLong (1998) characterizes patch sizes resulting from historical disturbance for areas of northern British Columbia using size classes and averages. The maximum sizes were found to be less than 10,000 hectares for most areas, although some plateau areas had maximum fire sizes of 20,000 to 40,000 hectares. Although these maximum fire sizes are less than those found in other studies of northern forests, mountainous topography and a forest mosaic that includes wetter, cooler stands likely limits the size of fires in these areas.

The Forest Practices Code Biodiversity Guidebook (BCMOF 1995) also provides information on patch size distributions using discrete size classes for various disturbance regimes. However, these are intended as size targets for harvest areas rather than a pure characterization of a disturbance regime, and represent an attempt to compromise between mimicking natural disturbance, and accommodating operational and social constraints associated with harvesting. DeLong (1998) points out that some of these patch size targets are much lower than estimated sizes from fire history studies.

1.4 Recent Examples of Natural Disturbance Simulation in Forest Models

The integration of natural disturbance explicitly into forest models is relatively recent. Van Wagner (1983) provides one of the first examples of explicit disturbance simulation in a non-spatial timber supply model. Stochastic fire events were used to demonstrate that when harvest rates are maximized without considering disturbance, the resulting losses to timber supply are greater than the actual volume burned. He further demonstrated that when harvest rates are reduced below this maximum, the harvest rate can become relatively insensitive to the amount of fire. Reed and Errico (1986) reached similar conclusions using a deterministic fire model, and showed that even modest rates of disturbance can have a dramatic impact on timber supply. Boychuck and Martell (1996) demonstrated that keeping a buffer stock of timber in response to natural disturbance risks can produce stable and in some cases larger long-term harvest rates. They emphasize that the buffer stock could not be located spatially, but that it is reflected in overall changes in the age class structure of the forest.

Examples of spatially explicit forest models that incorporate natural disturbance also exist. Boychuck and Perera (1997) used FLAP-X, a raster-based simulator that uses simple stochastic models of natural disturbance, to demonstrate long-term frequency distributions of percent old-growth and recently disturbed area. Lessard (1998) developed a process-based model that simulates forest growth, fire, and bark-beetle activity on a rasterized stand of white spruce to show the impacts of harvesting and fire suppression. LANDIS, described in Gustafson et al. (2000) simulates ecological dynamics including various forms of disturbance and their interactions. It is a raster-based simulator and the authors present an example where the effects of several harvesting strategies are tested. Kurz (2000) developed the polygon-based simulation tool TELSA, and demonstrated the effects of harvesting and stochastic disturbance on wildlife habitat patterns. SELES (Fall and Fall 2001) provides a raster-based environment for simulating stochastic events across a landscape, and provides a high-level programming language that allows users to develop their own disturbance models based on empirical data or more complex representations of disturbance processes. It has been applied to several landscapes in British Columbia to demonstrate landscape patterns resulting from forest growth, disturbance and harvesting (e.g. Fall 1999, Fall et al. 2001). Delong (2002) conducted simulations using SELES to provide estimates of the natural range of variation of landscape conditions for disturbance regimes in the Prince George Forest Region.

The issue of risk and uncertainty in models such as these has also been examined. Risk can be defined as the expected loss due to a particular hazard for a specific area and reference period, where the expected loss is the product of the damage and its probability of occurrence. Using this definition, Gadow (2000) demonstrates ways in which risk analysis can be applied to forest management problems, pointing out that applications of risk analysis are rare in forest planning.

Risk can also be defined as the probability of an outcome occurring in a given time period (Powers and Xie 2000). Using a definition of risk similar to this, Armstrong (2000) assessed the risk of timber supply sustainability alongside stochastic natural disturbance, using a non-spatial model applied to an area of boreal forest in northern Alberta. A range of harvest targets were tested, and the proportion of simulations where the targets exceeded the calculated AAC through time were reported. These proportions were then interpreted as a probability, and were used to demonstrate that the appropriate harvest level decreases as a company's tolerance for timber supply risk decreases, or as the time period of concern increases. Furthermore, it was concluded that the only harvest target that would not exceed the calculated timber supply at any time with absolute certainty would be zero.

Even with the above examples of disturbance simulation within forest models, examining the effects of various harvesting strategies alongside disturbance within a spatially explicit model still has considerable room for research (Nelson 2003a). Although the risk associated with harvest rates has been demonstrated by Armstrong (2000), different approaches to this problem still exist. The idea of buffering against the effects of natural disturbance on timber supply has been put forward by others (Boychuck and Martell 1996, Nelson 2003a) though ways of quantifying this buffer and the dynamics of buffer stocks through time have not been demonstrated. Although general effects of disturbance suppression have been simulated (Lessard 1998, Kurz 2000) more complex assumptions around our abilities to suppress natural disturbance events have not been examined. The impacts of disturbance on landscape attributes that reflect non-timber values has been examined in many of the examples cited above. These attributes remain interesting and critical measures to track, given their importance to society. Likewise, the impact of disturbance on the cash returns from timber harvesting is another critical factor. When coupled with an examination of various levels of disturbance and suppression effectiveness, examining economic impacts can provide a measure of the value of suppression, as well as the cost of disturbance itself.

1.5 Research Objectives

The objectives of this thesis are:

1. to quantify the risk associated with various harvest rates from fire disturbance uncertainty,
2. to quantify timber supply 'buffers' required to reduce the risk of harvest disruption,
3. to examine the impacts of harvesting and natural disturbance on landscape attributes such as late-seral inventories and patch sizes,
4. to examine the effects of suppressing natural disturbance on timber supply and landscape attributes, and
5. to quantify the cost of reducing risk, and the economic benefits of suppression.

2.0 Study Area Description

This chapter describes the study area used in the thesis. The types of forests contained within the study area are first described, followed by the natural disturbance characteristics of the area. Finally, historical and current forest management activities are reviewed.

2.1 Forest Cover and Natural Disturbance

Block 4 of Tree Farm License 48 is located in the Dawson Creek Forest District and is the study area in this thesis. The landscape is adjacent to the community of Chetwynd and contains forest stands that are within the Engelmann Spruce-Subalpine Fir (ESSF), Sub-Boreal Spruce (SBS), Boreal White and Black Spruce (BWBS), and Alpine Tundra (AT) biogeoclimatic zones. Tree species include lodgepole pine (*Pinus contorta*), trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*), hybrid spruce (*Picea engelmannii x glauca*) and black spruce (*Picea mariana*). Engelmann spruce (*Picea engelmannii)* and subalpine fir (*Abies lasiocarpa*) also occur at higher elevations. Figure 2.1 shows the location of the study area.

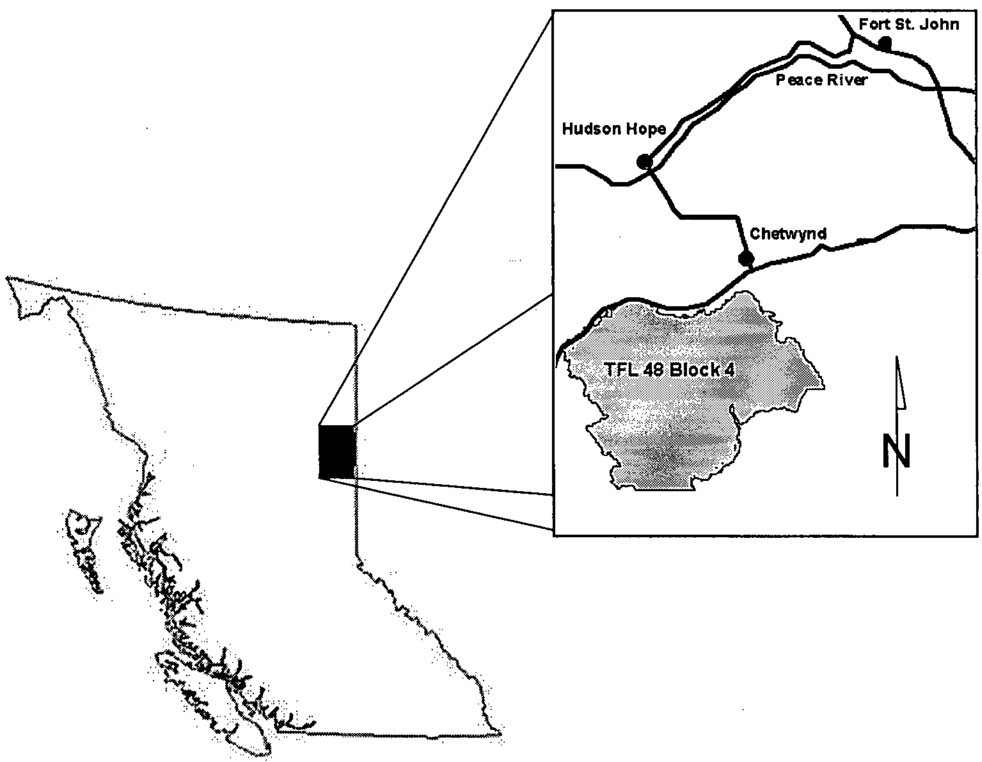


Figure 2.1. Location of the study area (not to scale).

Fire is the most significant cause of natural disturbance in the study area, accounting for the majority of non-recoverable losses (Canfor 2001). The study area falls within the Prince George Forest Region where DeLong (1998, 2002) estimated natural disturbance rates and patch size distributions. Fifteen different disturbance regimes are classified by DeLong for the region, and are referred to as Natural Disturbance Units (NDUs). Four of these NDUs occur in the study area, as shown in Figure 2.2. A summary of the disturbance characteristics found in each of these regimes is shown in Table 2.1.

Table 2.1. Disturbance parameters of NDUs within TFL 48 Block 4.

Natural Disturbance Unit (NDU)		Area (ha)	Disturbance Cycle (years)	Average Disturbance Size (ha)	Range of Disturbance Sizes (ha)
Boreal Plains (Upland)		64,530	100	200	0 - 41,787
Boreal Foothills	Valley	75,683	120	90	0 - 2691
	Mountain	94,880	150	80	0 - 2691
Wet Mountain		53,493	900	62	0 - 1082
Total		288,586			

Wildfire was confirmed to be the predominant disturbance agent in all of the disturbance regimes, with the exception of the Wet Mountian NDU. In this NDU, stands are more often subject to endemic levels of various insects and diseases, including spruce beetle (*Dendroctonus rufipennis*) and western balsam bark beetle (*Dryocoetes confusus*). Larger outbreaks of spruce beetle do periodically occur, though these events typically only cause shifts in species composition towards subalpine fir dominated stands, rather than complete stand replacement (Rosen 2002). This results in open, multi-aged stands dominating the landscape, which may only be subject to stand-replacing wildfires at intervals of up to 1000 years or more.

The Boreal Foothills NDU is dominated by large wildfires, resulting in large patches of even-aged forest. Historically the amount of old forest was highly variable at the watershed level, however a quantity of old forest was always present to some degree at the landscape level. Fire control in this NDU may have slowed the natural disturbance rate, increasing the amount of old forest in areas not subject to timber harvesting, and reducing large areas of fire-origin stands. The Boreal Plains NDU is also dominated by fire with similar patterns to those in the Boreal Foothills, although fires are characterized as being more frequent and much larger.

Local foresters report that all fires in the study area are subject to suppression. In the last 15 years it is estimated that approximately 15,000 cubic meters of timber volume have been lost to fires. Although wind damage can also occur in the study area, it rarely causes stand-replacing events and mainly consists of occasional fringe damage adjacent to harvested areas (Rosen 2002).

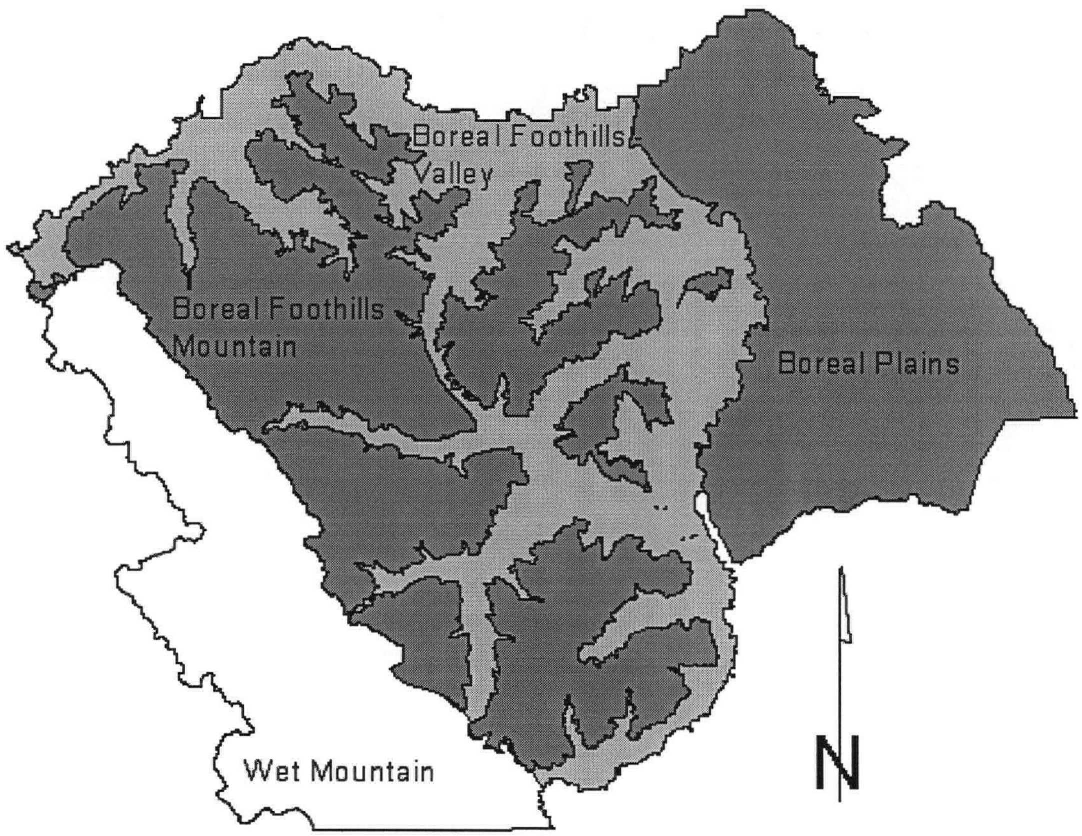


Figure 2.2. Natural disturbance regimes of the study area (not to scale).

2.2 Forest Management

In northern forests harvesting began in an exploitative fashion using diameter limit harvesting that targeted the removal of spruce, with little attention paid to silviculture. Clearcutting and planting eventually replaced previous practices, with opening sizes sometimes reaching over 1,000 hectares, and occasionally over 10,000 hectares for salvage operations (Kimmins 1998). In many cases these larger openings lacked any retention of mature forest (BCMOF 1995).

More recently, harvesting has been subject to the restrictions of the Forest Practices Code, with opening sizes in many areas constrained to less than 60 hectares (BCMOF 1998, Kimmins 1998). In some areas, however, larger patches have been created as a result of salvage operations (DeLong 2002). Forest management may be changing the spatial patterns and structure of forest ecosystems on the landscape. By suppressing fire activity, disturbance rates are reduced (DeLong 2002) and when combined with harvesting, disturbance rates are less variable and become more focused on older stands (Andison 1996). The amount of old forest in areas not subject to harvest increases, and a decrease in the occurrence of large fire-origin stands across the landscape also occurs. With the spatial arrangement of harvesting that was promoted under the initial implementation of the Forest Practices Code, the size and variability of patches was reduced (DeLong 2002). Current efforts to introduce harvesting based on natural disturbance emulation principles (BCMOF 1995, DeLong 2002, Kimmins 2001) may begin to reduce the structural changes occurring on these landscapes.

3.0 Methods

Methods used to simulate both harvest scheduling and natural disturbance are outlined in this chapter, as well as identification of the indicator variables used to record results. The modelling environment is introduced, which is based on the FPS-ATLAS harvest-scheduling simulator. The data sets used to study the interaction between harvest scheduling and disturbance are described. Two data sets are used, one that represents the TFL 48 Block 4 study area introduced in Section 2, and another that represents a smaller hypothetical forest that provides a simpler environment for exploring a wide range of scenarios. The smaller database is used for model development and testing, and the larger Block 4 database is used to demonstrate the application of the model to a practical-sized problem.

3.1 Harvest Scheduling Simulation

Harvest scheduling in this thesis uses the FPS-ATLAS model version 6.0.2.0 (Nelson 2003b). FPS-ATLAS is a polygon-based harvest-scheduling simulator that allows for modelling with spatial constraints including adjacency, seral stage levels and spatially located reserves. Databases can be generated from GIS-based forest cover data, and further refined through polygon splitting (Nelson 2001), or by creating resultant polygons such as squares or hexagons (Nelson and Davis 2002). Polygons can be aggregated into pre-determined blocks based on tactical plans or using patch building algorithms (Nelson 2001). Polygons are assigned to vegetation types called Stand Groups, which relate the age of the polygon to attributes that include harvest volume, and specify the age at which harvesting or other treatments can be applied.

3.1.1 Grid Database

The Grid database is a hypothetical 4000-hectare forest that is broken into 400 square polygons, with each polygon representing 10 hectares. All polygons belong to either a natural or a managed Stand Group, with yield curves that were developed for lodgepole pine stands in the BWBS Biogeoclimatic zone contained within TFL 48 Block 4.

The Grid database consists of a timber harvesting land base (THLB), a non-timber harvesting land base (NTHLB), and two disturbance regimes as shown in Figure 3.1. Regime 1 is a 2000-hectare contiguous area that has a disturbance cycle of 100 years (average 1 % of the area disturbed per year). Regime 2 is also a contiguous 2000-hectare area, but has a disturbance cycle of 200 years (average 0.5% of the area disturbed per year). Regime 1 has an average disturbance size of 400 hectares while Regime 2 has an average disturbance size of 50 hectares. Given the relationship between the average rate, average patch size and total area, Regime 1 is expected to have an average of one disturbance event every twenty years and Regime 2 could be expected to have an average of one disturbance event every five years. The THLB and NTHLB each contain portions of the two disturbance regimes, as shown in Figure 3.1. Harvesting, when enabled, only occurs in the THLB. The NTHLB is assumed to be inaccessible. Other assumptions include harvesting subject to a 20-year adjacency constraint, minimum harvest ages set to correspond to a volume of approximately 100 m^3/ha (90 years in natural stands and 70 years in managed stands), and oldest-first harvest priority. Simulations use ten-year time steps for up to 400 years.

(a)

(b)

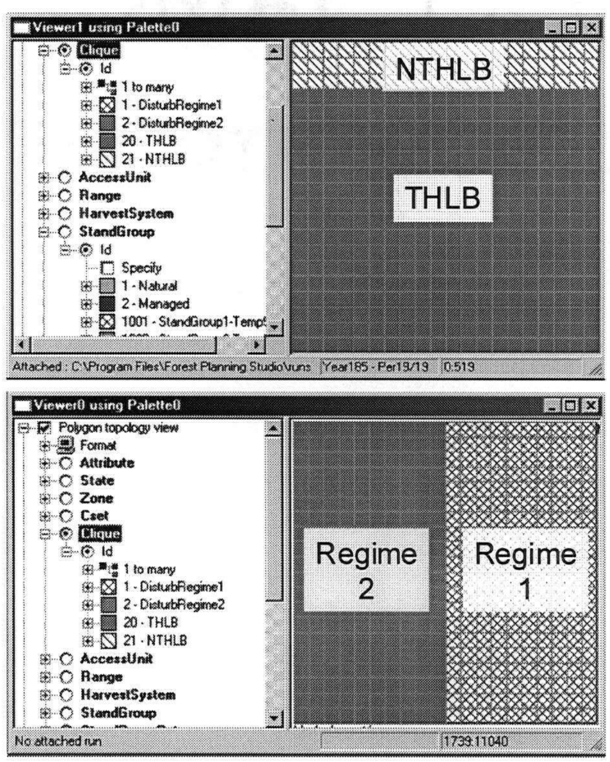


Figure 3.1. Sub-units of the Grid database. Timber Harvest Landbase (a) and Disturbance Regimes (b).

3.1.2 TFL 48 Block 4 Database

An FPS-ATLAS database was developed for Block 4 of TFL 48 (Seely et al. 2003). The database covers an area of approximately 288,000 hectares, and includes 70,777 polygons, which are classified into 141 Stand Groups. Yield curves for each Stand Group were developed using the FORECAST Ecosystem Simulation Program (Kimmins et al. 1999). Polygons were generated from GIS data using splitting techniques that eliminate very large polygons as well as 'sinuous' polygons such as those that follow riparian stands or road rights-of-way (Davis and Shannon 2003). The database is set up to harvest polygons in clusters, or "super-blocks", to more realistically represent operational harvest block configurations. A set of super-blocks that represents a 60-hectare target size for harvest units was used in this study. All polygons are assigned to one of the NDU disturbance regimes that are summarized in Table 2.1 on page 9.

A computer-generated road network was developed for the entire landscape consisting of approximately 7,000 km of road, described by 152,199 separate links (Anderson 2003). Estimates of road construction and deactivation for proposed harvest schedules were projected using this road network.

Minimum harvest ages for all Stand Groups were set to the age where mean annual increment is maximized. Stands were then prioritized for harvesting using a modified 'oldest-first' rule, where the number of years beyond the minimum harvest age is used to assign priority. Twenty-year adjacency rules were applied to harvesting, however this was constraint was relaxed for blocks less than 10 hectares, as well as for the first decade of harvesting where an excessive number of stands were constrained by this requirement. Simulations were conducted in ten-year time-steps, with all activity scheduled at the mid-point of the period. Simulation lengths of 300 years were used. The period length and time horizons were chosen based on balancing the need to explore long time horizons, and the limits of computational capacity. These parameters closely resemble those used for other studies of this type. The large size of the TFL 48 Block 4 database resulted in long model run times. Individual run times on an 800mhz processor with 512 mb of RAM took approximately 1.3 hours.

3.2 Disturbance Simulation

Disturbance consists of both large-scale stand-replacing events, and smaller scale endemic mortality and decay. Although this thesis is primarily focused on examining the effects of large-scale disturbances from forest fires, disturbance from small-scale endemic agents are also accounted for in the model, and are incorporated into the yield curves generated by FORECAST. These losses, which are assumed to result from insects and other forest pathogens, typically consist of mortality in 3-5% of the live stems in stands every 20-60 years, depending on the Stand Group. Operational adjustment factors (OAFs) were also applied to merchantable volumes to represent further reductions in volume recovery (waste and breakage) at the time of harvest, and in some cases additional losses occur in older stands due to increasing decay. The yield curves and endemic disturbance assumptions were developed as part of a larger research project on TFL 48 (Seely 2003), and were not developed by the author.

Larger-scale disturbance events were simulated using an option in FPS-ATLAS that pauses the simulation at each period. At each period, the user can interact with the land-base manually, or with an external application. This "interactive" option was utilized to link disturbance models with the harvest scheduling simulation and reporting functions of FPS-ATLAS. Details of the disturbance model are given shortly.

Salvage harvesting was simulated by making disturbed stands available for harvest. Salvaged stands received top priority for harvesting, relative to the sorting method used. For example, if sorting by age is used, disturbed stands are prioritized by age ahead of the undisturbed stands in the harvest queue. It is also assumed that stands are only available for salvage for one period following the disturbance, and if not salvaged, become non-recoverable losses. In simulations where salvage harvesting occurs, both the natural and managed stands are assumed to yield 70% of their volume.

An overview of disturbance and harvesting within FPS-ATLAS is shown in Figure 3.2. Using the process in Figure 3.2, stands are disturbed and made available for harvest at their current age, but in a different Stand Group that can yield a reduced volume to represent disturbance losses. If salvaged by FPS-ATLAS, the stands are converted to a managed Stand Group. If not salvaged, the next execution of the disturbance model re-sets the stand to an unmanaged Stand Group. In this way, salvaged stands may have higher yields during the next rotation than un-salvaged ones, plus they have a 'head-start' of one period of growth.

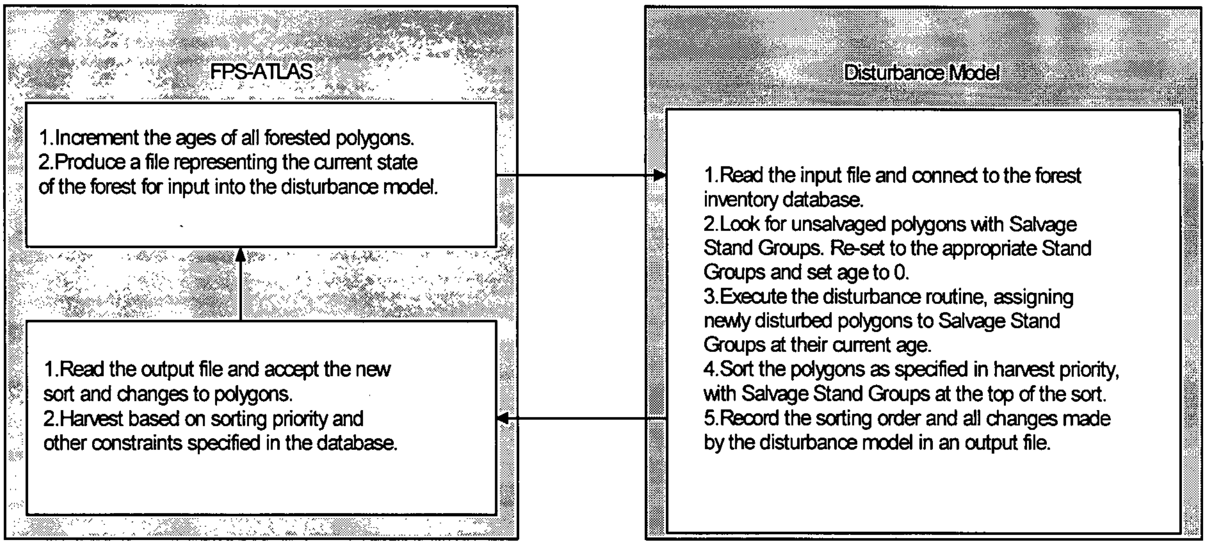


Figure 3.2. Harvesting and disturbance routines repeated in each period during a simulation.

3.2.1 Description of the Disturbance Model

The disturbance model was developed using the Java programming language. All disturbance is assumed to consist of stand-replacing wildfires, and disturbance occurrence is assumed to be independent of stand age. For the boreal forest, age-independence has been widely suggested (e.g. Johnson et al. 1998, Frelich 2002) and is a common assumption in natural disturbance simulation (e.g. Armstrong 1999, Boychuck and Perera 1997, Martell 1994, van Wagner 1983). Cumming (2000) demonstrated that the hazard of burning likely does change with fuel type, based on fire occurrence rates for deciduous, spruce and pine stands. While I have not included a changing burn rate between stand types, the model does allow for multiple, spatially located disturbance regimes that are assumed to reflect, among other things, the unique conditions created by the mosaic of stands that occur in each area. In addition, vegetation types such as swamps or non-commercial brush that are not normally subject to these types of disturbance can be excluded. Because of the age-independent assumption, re-burning of polygons in the same simulation period can occur. While this may be a rare occurrence in the same year, simulations that involve multiple-year periods would have an increased chance of re-burns. While the issue of re-burning has been addressed using adjustment factors to the disturbance rate (e.g. Andison 1996), I have simply allowed it to occur in the model, by making stands eligible for disturbance once the current event is complete.

Rates of natural disturbance fluctuate through time. Fluctuations are caused by factors that include the randomness of events that initiate disturbance, such as lightning, and fluctuations in the conditions that facilitate disturbance, especially weather, often leading to high variability in rates. A method for varying disturbance rates has been developed here that incorporates recent work on disturbance occurrence (cited below), and expert advice (Cumming 2003). Unless otherwise stated, probability theory and statistical methods have been taken from Cameron and Trivedi (1998).

Variability in annual disturbance rates has been simulated by mimicking historical variation (e.g. Kurz 2000), or by generating random variates from mathematical distributions. Distributions can range from simple probabilities for two discrete rates of disturbance (Boychuck and Martell 1996) to more complex continuous distributions such as the lognormal (Armstrong 1999). Variability in disturbance rates can also be introduced by varying the number of disturbance events per unit time rather than directly varying the overall area affected. The Poisson distribution has been used to describe the occurrence of disturbance events (e.g. Fall 1998, Boychuck and Perrara 1997). The Poisson distribution can describe a number of events per unit time, assuming the inter-arrival time of events follows a negative exponential distribution. The probability density function is written as:

(1) $$f(y) = \frac{e^{-\lambda}\lambda^{y}}{y!}$$

where results are restricted to positive integers and the average or expected value is λ. It is additive and scaleable making it easy to apply to a variety of spatial and temporal scales. For example, if a Poisson process has a mean value of λ events per hectare per year, then the process over ten hectares would be a Poisson process with a parameter $10 \cdot \lambda$, as would the process per hectare per ten years. If several independent Poisson processes exist, with expected values of λ_1, λ_2, λ_3, λ_4, the sum of the outcomes of these processes will also be Poisson distributed with an expected value of $\lambda_T = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4$. If a draw is made from this 'superposition' process, thinning can be applied to the events represented by the draw, allocating each of them to one of the sub-processes, based on probabilities. The probability of an event being allocated to process j would be equal to λ_j / λ_T. The events allocated to this sub-process over several draws from the superposition would still be independently Poisson distributed with a mean of λ_j (Ripley 1987).

As the variance of a Poisson process is by definition equal to that of the mean, it has only the single parameter λ, which in the case of disturbance event simulation would be the expected number of events on a given area during a specific time period. This can be determined from historical records, or by calculating the expected number of events from the relationship:

(2) $$\text{Expected Number of Events} = \frac{a \cdot b \cdot c}{d}$$

where: Average Disturbance Rate (decimal proportion per year) = a

Area (ha) = b

Period Length (years) = c

Average Patch Size (ha) = d

Depending on the size of the landscape relative to the disturbance size distribution, the number of expected events per year or time period (Equation 2) can become low, even much less than 1. Disturbance rates might still be characterized as high, which may seem paradoxical. This is correct however, since the question begins to change from *how much* of the landscape is disturbed each period, to *how often* all or most of it is disturbed (Cumming 2001a). Many landscapes might lie somewhere in between these two situations. Using a distribution such as the Poisson that is restricted to integer values correctly simulates event occurrence even on small landscapes, by providing many random draws of zero, along with rare events that would typically lead to catastrophic losses.

While the Poisson distribution provides a convenient approach to simulating the number of disturbance events per unit time, it likely oversimplifies variability on most landscapes. One assumption that (stationary) Poisson processes need to satisfy, is that the probability of events occurring through time remains constant, allowing the variance in values to be modelled as equal to the mean. As weather fluctuations can create wide ranging and unpredictable conditions, it seems unlikely that this condition would be met. Extra-Poisson variability in disturbance event occurrence was demonstrated in Cumming (2000) for an area of boreal forest, and event occurrence was instead characterized with a negative binomial distribution with a probability density function:

(3) $$f(y) = \frac{\Gamma(y+\alpha^{-1})}{\Gamma(y+1)\Gamma(\alpha^{-1})}\left(\frac{(\alpha^{-1})}{\alpha^{-1}+\mu}\right)^{\alpha^{-1}}\left(\frac{\mu}{\alpha^{-1}+\mu}\right)^{y}$$

and a variance:

(4) $$\sigma^2 = \mu + \alpha\mu^2$$

where μ is the expected value, α is an over-dispersion parameter, and $\Gamma(\cdot)$ is the Gamma Function (an extension of the factorial function f(x)=x! to non-integer values, not to be confused with the Gamma distribution). When $\alpha=0$, Equation (3) reduces to the Poisson distribution with $\lambda=\mu$.

The negative binomial distribution can also be modelled as a Poisson-gamma mixture, where λ has a multiplicative term that follows a gamma distribution.

The gamma distribution has a scale parameter ϕ, a shape parameter δ, returns an expected value of δ/ϕ and has a variance of δ/ϕ^2. For integer values of δ, it can be thought of as the sum of δ draws from an exponential distribution each having an expected value $1/\phi$.

The probability density function is:

(5) $$g(v) = \frac{\delta^{\phi}}{\Gamma(\delta)} v^{\delta-1} e^{-v\phi}$$

To return an expected value of 1, Equation (5) can be reduced to a single parameter distribution by setting $\delta = \phi$. When this distribution is included as a multiplicative term for λ in the Poisson distribution in Equation (1), the negative binomial distribution can be derived in the form given in Equation (3), where $\alpha = 1/\delta$.

To model the variation in disturbance rates, I have simulated fire occurrence using a negative binomial distribution. I use a Poisson distribution with a mean based on the expected numbers of events, and a multiplicative factor that is gamma distributed with a mean of 1. At each period, a gamma variate is drawn that represents extra-Poisson variation. A common gamma variate is used across all regimes in each period since extra-Poison variation is likely due to weather, which I assume affects all areas in a similar way. The gamma draw multiplies each of the expected number of events in regimes, either increasing or decreasing them. Poisson variates are then drawn based on the adjusted λ values, and these are implemented as disturbance events in each of the associated regimes, using stochastically generated patch size targets (described shortly). In this way, the volatility of the rate becomes uniquely related to the relationship between event occurrence, event size and landscape size, rather than simply being a fixed or varying percentage of the landscape.

The gamma distribution is parameterised based on estimates of δ and ϕ. To simplify the generation of gamma variates, the δ and ϕ parameters were restricted to integers, and the gamma variate was simulated as the sum of δ exponential draws with a parameter $1/\phi$. For example, assume two regimes have an expected number of disturbance events per year of 3 and 5 respectively ($\lambda_1 = 3.0$, $\lambda_2 = 5.0$). If the over-dispersion parameter is 15 ($\delta = \phi = 15$ which translates to an α value of 0.06666 repeating) a gamma draw based on these parameters is made each year, which is multiplied by the λ values. If the gamma draw in one year was, for example 1.2, the expected number of events in that particular year would be 3.6 and 6.0. Poisson draws to determine the actual number of events are then made based on $\lambda'_1 = 3.6$ and $\lambda'_2 = 6.0$.

Fire history studies can be conducted to provide estimates of over-dispersion for specific areas (e.g. Cumming 2000, Cumming and Wong 2002). Since this information was not available for this thesis, sensitivity around this parameter will be tested to determine its effect on model output.

Once a disturbance event is initiated, it grows into a patch based on a stochastically generated patch size target. A random polygon is first chosen as a seed for an event, and the event spreads to adjacent polygons until either the patch size target is reached or there are no more eligible adjacent polygons. As each polygon is disturbed, it's adjacent polygons are added to a queue, which are evaluated in sequence for their eligibility for disturbance. Eligible polygons are disturbed and made ineligible for being re-disturbed until the current event has finished.

Patch size targets in these simulations are drawn from an exponential distribution, which is parameterised based on average patch sizes determined for the given regime. The exponential distribution has a probability density function:

(6) $$f(y) = \lambda e^{-\lambda y}$$

with an expected value of $1/\lambda$ and a variance of $1/\lambda^2$.

Patches are allowed to spread in any direction, allowing them in most cases to achieve their target size. Spread direction was not considered in the patch building process, as the model is simply trying to implement a patch on the landscape, rather than mimic the behavior resulting from a specific event such as a lightning strike. Also, shape characteristics such as area-perimeter ratio and orientation relative to slope, aspect or wind direction were not considered. Although patches will spread in a roughly circular fashion when all adjacent polygons are eligible, the exclusion of ineligible vegetation types such as swamps, as well as rivers and lakes, effectively creates "fire-breaks" on the landscape that lead to disturbance shapes that do relate to topographic factors.

3.3 Indicator Variables

Five indicator variables were tracked in all scenarios. These were percentages of late seral area, small patch area, growing stock, timber availability, and maximum sustainable even-flow harvest target. For scenarios on TFL 48 Block 4, a sixth indicator variable, cash-flow, was added. To compare scenarios, indicator variables were examined across multiple runs in terms of average values and the range in results. Run numbers are assigned to each simulation based on the landscape, scenario and replication, and are summarized in Appendix 1. Graphs showing the dynamics of these variables through the simulations are presented in some cases. The changes to landscape condition resulting from different scenarios are also demonstrated by examining the average and range over the last 100 years of simulations. A 100-year time-span was examined to capture as much of the variability as possible, while excluding results that are an artifact of the starting conditions or transition periods during which the landscape is responding to scenario changes. Details of the indicator variables and their interpretation are described below.

3.3.1 Seral Stage Levels and Patch Sizes

Seral stage classes are defined as shown in Table 3.1. Seral stages were examined by tracking the percentage of area in the late seral class. Late seral percents were examined for the landscape as a whole, as well as within specific parts of the landscape.

Table 3.1. Seral stage classes.

Seral Stage	Age (Yrs)
Early	0-40
Mid	41-100
Mature	101-140
Late	141+

Patches are contiguous areas of the same seral stage. The area in small patches (0-50 hectares) was tracked, as a measure of fragmentation on the landscape. Because patches can and often do span the boundaries of disturbance regimes and other landscape divisions, patches are only tracked across the entire landscape, and include the area in small patches for all seral stages combined.

3.3.2 Growing Stock and Timber Availability

Growing stock in this analysis is the total timber volume, or standing inventory, regardless of minimum harvest age, site productivity and accessibility. It is the sum of the volumes returned by the yield curves for all stands in a given area, at a specific time. Growing stock levels for the whole forest and in specific areas are reported.

Timber availability is the maximum quantity of timber that is actually available for harvest in each period considering all constraints, and the harvest from previous periods. It does not represent a maximum flow, since harvesting up to the availability in any one period would likely mean very little or no timber is available in the next period. For a given scenario and harvest target, availability is calculated by iterating through the schedule, one period at a time, allowing the scheduler to harvest as much timber as it can in a given period (Davis and Boyland 2003). For example, availability in the sixth decade of a harvest flow of 68,000 m^3/decade would be tested by harvesting 68,000 m^3 for the first five decades, then setting the target for the sixth decade to an impossibly high number, and recording the amount that could actually be harvested. The procedure is shown in Figure 3.3.

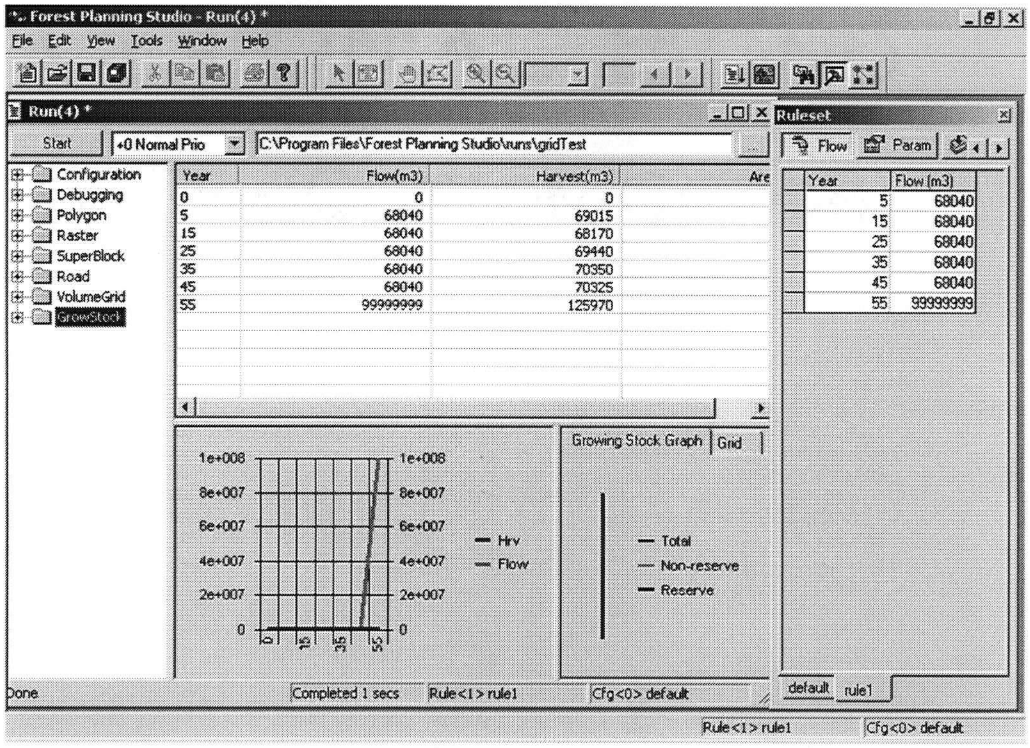


Figure 3.3. Calculating timber availability in FPS-ATLAS. In this iteration, the scheduler shows 125,970 m^3 of available timber in Year 55 of the simulation.

To find the availability for a harvest schedule, this procedure must be conducted for every period. A constraining point occurs in periods where the availability and the harvest are the same, and indicates an absence of "slack" in the system during that period. During simulations that included disturbance modelling, multiple runs were conducted to show the range of variation in timber availability. Availability of timber for the whole forest and in specific areas is reported.

3.3.3 Sustainable Harvest Target

Harvest targets that are consistently unreachable do not represent a reasonable management objective, and iteratively reducing targets until a sustainable rate is found is one of the most basic uses of a harvest scheduling simulator. As targets are systematically reduced, the frequency and magnitude of shortfalls usually decrease, although the stochastic nature of the disturbance model makes each run unique. Deciding if a target is acceptable is more difficult when many repeated simulations yield stable harvest flows far into the future, yet for some runs the harvest is unachievable in some periods and rarely, when disturbance occurs at the right times and in the right places, a pronounced shortfall over multiple periods still occurs. The complete elimination of all shortfalls using stochastic disturbance simulation can often involve drastic reductions to harvest targets. For example, Armstrong (2000) concluded that the only harvest target that would not exceed the calculated timber supply in any period with absolute certainty would be zero. Risk assessment is therefore a logical extension to the problem of quantifying an acceptable harvest target.

In this thesis, risk tolerance will be defined as less than a one-in-ten chance of a shortfall of greater than 10% of the harvest target in any ten-year time period. The proportion of runs that fail to achieve 90% of the volume target at any period are recorded and expressed as a proportion, and harvest targets are determined to be sustainable where this proportion falls below 0.1.

To further assist choosing an appropriate harvest target, a regression line was determined using the relationship between the harvest target and the proportion of runs that meet the targets. A logistic regression model was used (Powers and Xie 2000), which involves transforming the proportions observed according to the logit function:

$$y' = \ln(y/(1-y)) \qquad (7)$$

The logit model is commonly used in medical research, where a proportion such as a death or survival rate is predicted base on a continuous variable such as a dosage level of medicine. The logit model allows the values of the dependent variable to assume any real number, rather than being restricted to values between zero and one. The transformation is demonstrated graphically in Figure 3.4.

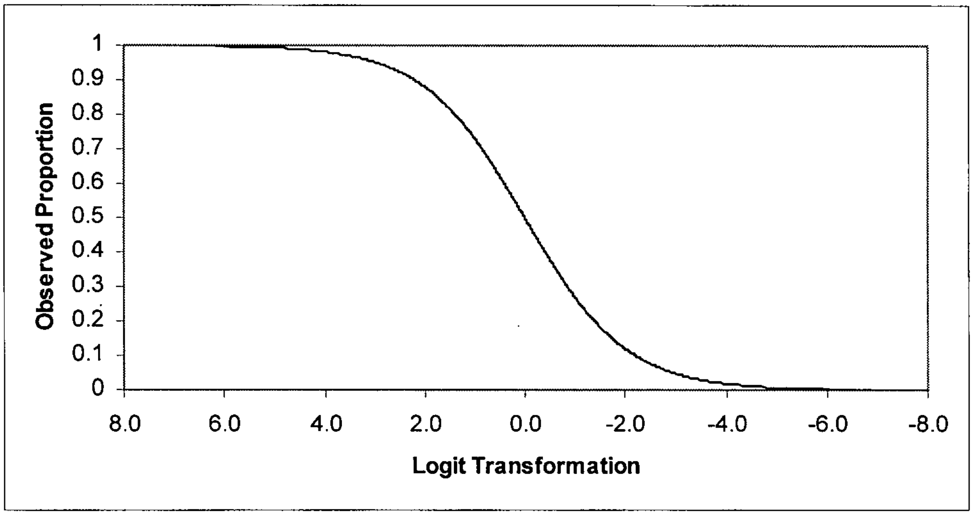


Figure 3.4. Logit transformation of proportions.

A linear relationship between the harvest target and the logit transformation of the proportion was determined, which is then expressed in terms of the original dependent variable as follows:

(8) $$y = \frac{e^{b_0 + b_1 x}}{1 + e^{b_0 + b_1 x}}$$

Analyses were based on a uniform distribution of harvest targets, with each target tested with an equal number of runs. An example is shown in Figure 3.5.

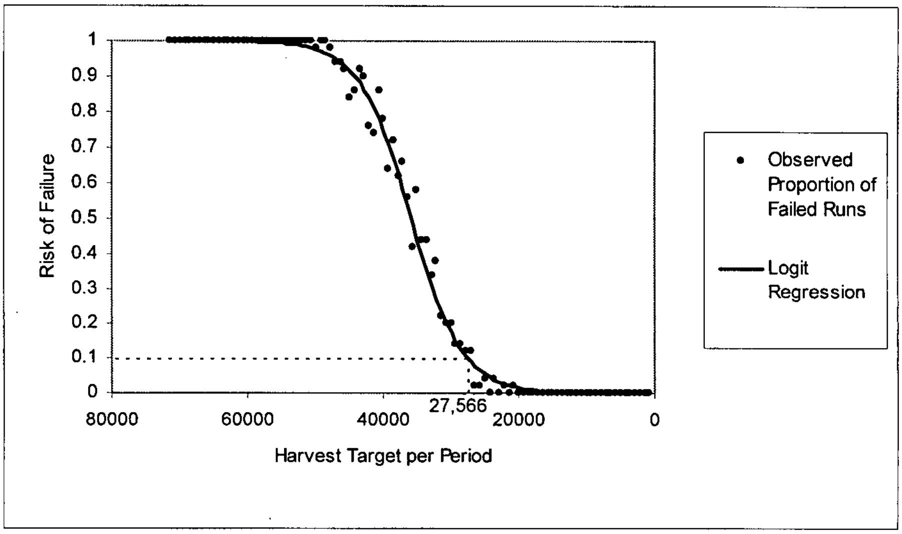


Figure 3.5. Example of observed proportion of failed runs and regression line.

Figure 3.5 shows an example of 100 uniformly distributed harvest targets that were each tested for sustainability using 50 simulations. In Figure 3.5 the risk of failing to meet the harvest targets is 0.1 when the harvest target is approximately 27,566 m^3 per period.

Run numbers were assigned to each simulation based on the landscape, scenario and replication, and are explained and summarized in Appendix 1.

Ten runs per harvest target were tested for most scenarios, using a strict even-flow policy, due to the limits of processing time. However, in some scenarios more precise estimates of risk using up to fifty runs per harvest target were also tested.

3.3.4 Cash-Flow

For TFL 48 Block 4, estimates of costs and revenues for delivered wood were used to determine profit for each period in the harvest schedule. Curves were generated for each of the 141 Stand Groups that represent the revenue per cubic meter of timber delivered to the mill. Prices for log grades are summarized in Table 3.2.

Table 3.2. Revenue per m^3 for log grades.

Log Type	Revenue per m^3
Pulp	$35
Large Sawlog	$85
Small Sawlog	$65
Peeler	$100

The prices in Table 3.2 resemble relative log values in the BC interior, although log values under current market conditions are somewhat lower. For example, the log prices reported by the BC Ministry of Forests Revenue Branch for 1 November 2003 to 31 January 2004 (BCMOF 2004) show average interior sawlog prices of $56.72, average peeler prices of $83.19, and average pulp prices of $30.56.

Revenue curves were generated using the FORECAST output files that also provide the yield curves in the FPS-ATLAS database. The quantity of merchantable timber in the four log grades was calculated, based on the size and merchantable volume reported by FORECAST for each stem in a given hectare. Assumptions used in calculating the volume in each log grade are summarized in Table 3.3.

Table 3.3. Assumptions used to calculate volume in each log grade.

Species	Log Grade Assumptions
White, Engelmann, and Hybrid Spruce	• For stems over 30cm DBH, 20% of volume is peeler grade, 30% is large sawlog, and the remaining volume is small sawlog. • For stems under 30 cm DBH all volume is small sawlog.
Lodgepole Pine	• For stems over 30cm DBH, 50% of volume is large sawlog and 50% of volume is small sawlog. • For stems under 30 cm DBH all volume is small sawlog.
Subalpine Fir	• For stems over 30cm DBH, 25% of volume is large sawlog, 25% is small sawlog and the remaining volume is pulp. • For stems under 30 cm DBH, 50% of volume is small sawlog and 50% of volume is pulp.
Trembling Aspen	• All volume is pulp.

Using the assumptions in Table 3.2 and Table 3.3, an example revenue curve for a mixed conifer-deciduous stand is shown in Table 3.4.

Table 3.4. Example revenue curve for a mixed conifer-deciduous stand.

	Volume per hectare (m^3)					Revenue ($)	
Age	Large Sawlog	Small Sawlog	Peeler	Pulp	Total	Per ha	Per m^3
10	0	0	0	0	0.00	$0.00	$0.00
20	0	0.22	0	0.12	0.34	$18.50	$54.41
30	0	4.67	0	8.79	13.46	$611.20	$45.41
40	0	28.11	0	30.07	58.18	$2,879.60	$49.49
50	0	71.4	0	49.83	121.23	$6,385.05	$52.67
60	0	138.47	0	75.53	214.00	$11,644.10	$54.41
70	13.84	203.8	9.23	94.36	321.23	$18,648.97	$58.05
80	34.24	264.87	22.83	97.91	419.85	$25,836.77	$61.54
90	110.94	211.02	73.96	70.14	466.05	$32,996.32	$70.80
100	141.48	238.07	94.32	0	473.87	$36,932.48	$77.94
110	160.84	268.06	107.23	0	536.13	$41,818.14	$78.00
120	176.46	294.1	117.64	0	588.19	$45,878.82	$78.00
130	180.46	300.76	120.3	0	601.52	$46,918.56	$78.00
140	190.84	318.06	127.23	0	636.13	$49,618.14	$78.00
150	198.55	330.92	132.37	0	661.84	$51,623.52	$78.00
160	204.15	340.25	136.1	0	680.5	$53,079.00	$78.00
170	198.23	330.38	132.15	0	660.77	$51,540.06	$78.00
180	201.43	335.71	134.28	0	671.42	$52,370.76	$78.00
190	203.44	339.06	135.62	0	678.12	$52,893.36	$78.00
200	205.22	342.03	136.81	0	684.06	$53,356.68	$78.00

The stand in Table 3.4 delivers a mixture of small sawlogs from the conifer component and pulpwood from the deciduous component during the early years. After age 80, the deciduous component of the stand begins to break-up, and a stand consisting of larger conifer stems develops, providing a mix of large and small sawlogs, plus peelers. As the proportion of large sawlogs and peelers rises and the pulp component drops, the revenue per cubic meter rises by roughly $30.

Although this example shows a dramatic decline in the amount of pulp from age 80 to 100, this results from the rapid decline in trembling aspen from the stand, which is the only source of pulp volume in this particular Stand Group. Other Stand Groups that include subalpine fir show pulp volumes that continue to accumulate with age, using the assumptions from Table 3.3. The value per m^3 also remains unchanged in this example after age 100, due to a stable proportion of products coming from the stand. Stand volume does continue to change however, keeping the value per hectare dynamic up to age 200. Other Stand Groups display different patterns in total volume and volume in each log grade, and this is only one example from the 141 Stand Groups used in the analysis.

Costs for harvest systems are summarized in Table 3.5.

Table 3.5. Harvesting costs (tree to truck).

Harvest System	Cost per m^3
Ground-based (Skidder/Cat)	$35
Cable (Highlead/Small Skyline)	$85
Mixed Cable/Ground-based	$65
Aerial (Helicopter)	$100

An additional $3 per m^3 was added to the harvesting costs to account for administration and planning expenses. $2000 per hectare was also charged for basic silviculture, based on the net productive area for all harvested polygons.

Road construction, deactivation and reactivation estimates are shown in Table 3.6.

Table 3.6. Road costs ($ per km).

Road Class	Costruction	Deactivation	Recactivation
Class 1 (Mainline)	$40,000	n/a	n/a
Class 2	$35,000	n/a	n/a
Class 3	$30,000	$2,000	$8,000
Class 4	$25,000	$2,000	$8,000

Only Class 3 and Class 4 roads are subject to deactivation, which is scheduled by FPS-ATLAS if a road is determined to be inactive for 20 years or more. Road maintenance is not included as a separate cost. Road maintenance is assumed to be included in the average per cubic meter per kilometer hauling costs, estimated at $0.10/m^3/km.

Once the revenue data were generated, the delivered wood value for each stand harvested was calculated. A separate program reads the volume harvested, the Stand Group, and the age of the stand from the FPS-ATLAS output, as well as the revenue curves, and calculates delivered wood revenues and costs for all harvested stands and sums them for each period in the schedule. As revenue curves are expressed in ten-year time intervals, revenue from stands harvested at specific ages were determined by linear interpolation. Note that the profit excludes all stumpage, royalties and taxes.

Profits (or losses) were discounted using various discount rates to obtain net present values. Discount rates represent the cost of waiting for future benefits to arrive, and the benefit of delaying future costs. Put another way, the discount rate represents our preference for present versus future consumption. Discount rates can include factors such as the opportunity costs of capital (what you could expect to gain from capital if you had it available for other uses over a period of time), risk (the risk of losing your investment if the forest was destroyed, damaged or made unavailable to harvesting) and inflation. (BCMOF 1999). Social discount rates for public decision making can incorporate other factors above those used in the private sector, including an opportunity cost of capital that reflects the cost to society of governments obtaining money through taxation (Conrad and Clark 1987). The BC Ministry of Forests uses a 4% discount rate for evaluating public sector forestry investment (BCMOF 1999). If timber supply is being managed on a sustained yield basis, discount rates are effectively zero, meaning future supply is valued equally to current supply. Although discounting may be inappropriate for many evaluations of forest management and sustainability, it does provide a reflection of what a private-sector purchaser might be willing to pay for an area of forest, based on cost and revenue projections.

4.0 Results

Analyses using the Grid database are presented first, followed by scenarios run on TFL 48 Block 4. Data from multiple runs are presented as single period averages, along with the maximum and minimum values to show the range of variation. Each period represents ten years of forest growth and disturbance, with all activity assumed to occur at the mid-point of each period.

The Grid forest was used to develop and test the model, and scenarios were modelled with forest growth only, forest growth with disturbance, and finally, growth, disturbance and harvesting. The sensitivity of the harvest rate to salvage logging, simulation length, shortfall tolerance and variability in disturbance occurrence is examined. The interaction between the two regimes in providing timber is demonstrated, and the precision of the regression estimate of risk is explored. Run numbers were assigned to each simulation based on the landscape, scenario and replication, and are summarized in Appendix 1.

The model is then applied to the Block 4 database. Scenarios that assume no disturbance and full historical disturbance, with and without harvesting are examined. Finally, the effects of disturbance suppression are tested. With the addition of cash-flow as an indicator variable, estimates of the cost of disturbance and the value of suppression are made.

4.1 Grid Database Scenarios

Scenarios that did not include harvesting were first run to examine disturbance simulation, and to warm up the model by 'growing' the forest in a way that creates landscape conditions that reflect the disturbance regimes being simulated. All stands were first set to an age of 0 years in the natural Stand Group. Forest growth, along with explicit disturbance was simulated over long time horizons of up to 400 years. The no-harvest runs were also used to validate some of the parameters and distributions specified in the disturbance model. Graphs demonstrating these validations are presented in this section. Final conditions from this set of disturbance only runs were used as starting conditions for a series of model runs that further validate model parameters and functions, test the sensitivity around parameters, and explore the differences resulting from various disturbance and harvesting scenarios.

4.1.1 Growth Only

To provide a baseline to demonstrate the development of stands resulting from the yield functions described in Section 2.1, a run was first conducted that assumed no harvesting or disturbance.

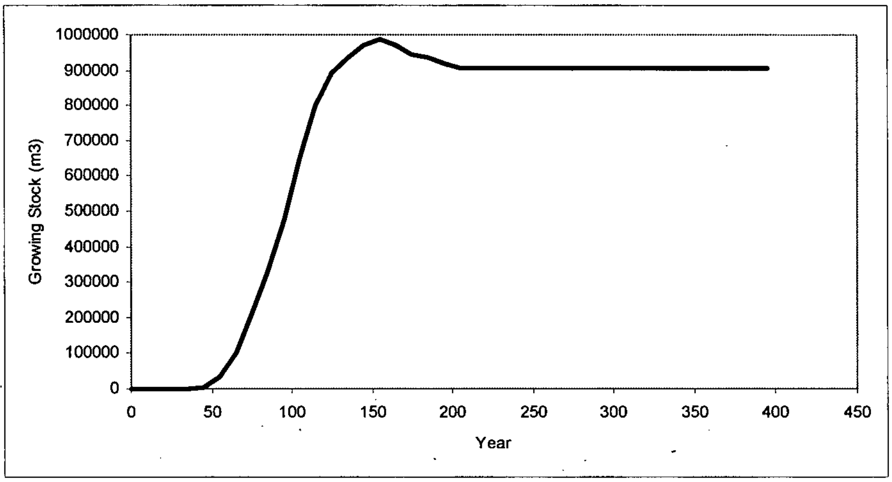


Figure 4.1 Growing stock – growth only scenario (Run 1.1.1d).

Figure 4.1 shows that growing stock rises steadily for the first 150 years of the simulation, to a peak of 988,000 m^3, which then falls slightly to 908,000 m^3 as stands reach an over-mature state and become subject to the endemic mortality agents that have been incorporated into the yield curve (described in Section 3.2). In this example, losses from endemic disturbance are assumed to equal growth after roughly 200 years. Other Stand Groups used in the Block 4 analysis may show further declines in volume with increasing stand age. As no activity occurs on the landscape aside from growth, other indicator variables such as seral stage percentages and patch size statistics follow a predictable pattern, with the landscape remaining in a single patch of 4000 hectares for the entire simulation, passing through the seral stage classes over time, until the entire landscape is in the late-seral class after year 140.

4.1.2 Growth and Disturbance

A series of disturbance only runs (Runs 1.2.1d-1.2.50d – see Appendix 1 for an explanation of run numbers) were then conducted using methods outlined in Section 2.0 assuming a negative binomial distribution of events per period with an α value of 0.2, and an exponential distribution of event sizes.

Disturbance parameters were first validated, by confirming the distribution of results from stochastic functions. Means and variances are shown in Table 4.1, and frequency histograms are shown in Figures 4.2 and 4.3. Data were summed from all periods combined across fifty runs.

Table 4.1. Expected and observed means and variances for disturbance statistics from fifty simulations. (Runs 1.2.1d-1.2.50d).

		Number of Events		Event Sizes		Disturbance Rate	
		Mean	*Variance*	*Mean*	*Variance*	*Mean*	*Variance*
Regime 1	*Expected*	*0.50*	*0.55*	*400*	*160,000*	*0.100*	-
	Observed	**0.47**	**0.53**	**401**	**162,410**	**0.095**	**0.041**
Regime 2	*Expected*	*2.00*	*2.80*	*50*	*2,500*	*0.050*	-
	Observed	**1.99**	**2.66**	**52**	**2,753**	**0.052**	**0.003**

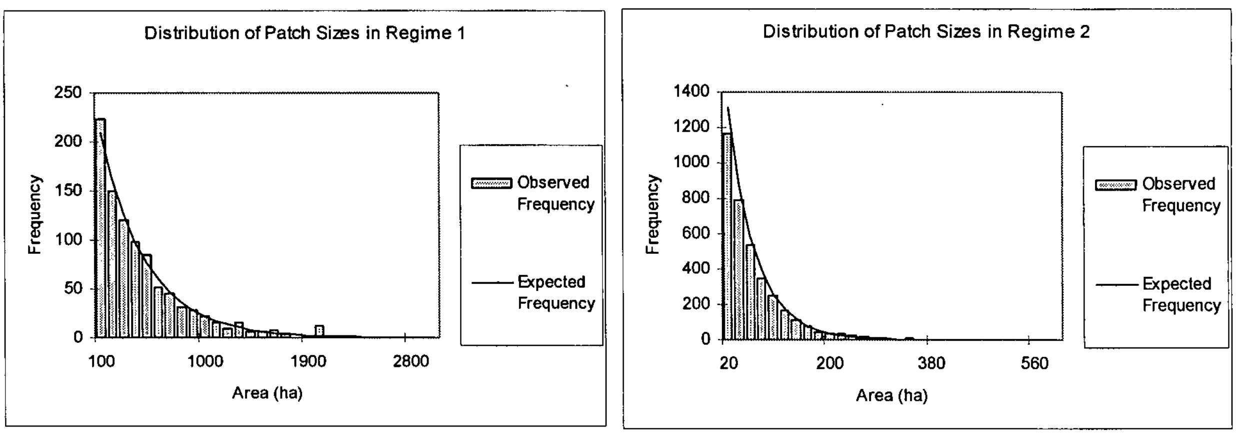
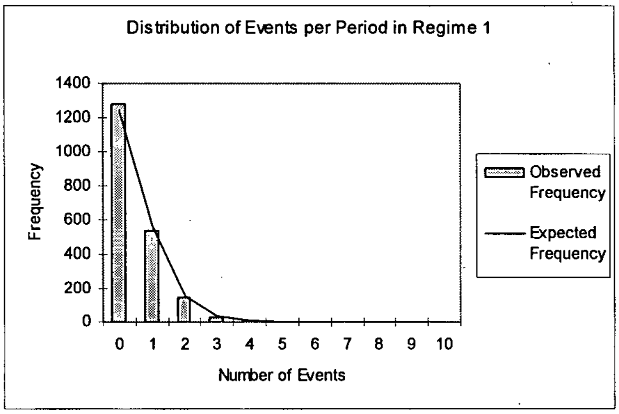


Figure 4.2. Observed and expected frequency of disturbance sizes from fifty simulations. (Runs 1.2.1d-1.2.50d).



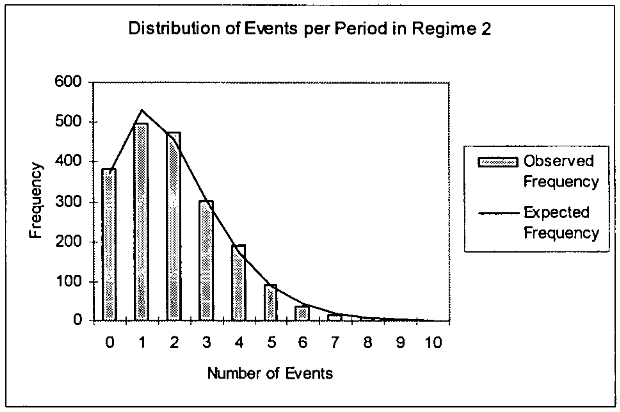


Figure 4.3. Observed and expected frequency of events per period from fifty simulations. (Runs 1.2.1d-1.2.50d).

Table 4.1 and Figures 4.2 and 4.3 demonstrate that the disturbance events and sizes modelled occur as expected, with means, variances and frequency distributions that closely resemble the theoretical targets. Regime 1 has disturbance events that are less frequent, but much larger than those in Regime 2, leading to a higher overall rate of disturbance in Regime 1. Although statistical methods could be used to further confirm distributions, this is unnecessary as the draws have actually been made from the distributions, rather than the result of processes for which a distribution is to be established. The relationship between the number of disturbances and their sizes is also confirmed as reflecting the average disturbance rate, which is within 5% of the expected rate for both regimes. However, the overall rate observed in Regime 1 has a much higher variance, demonstrating that with a lower expected number of events per period, disturbance rates become more volatile.

The only anomaly noted is a small spike in the frequency of 2000-hectare patches in Regime 1 seen in Figure 4.2. This is due to the size of the regime being 2000 hectares, which defines the largest patch size that can be simulated. Hence, the 2000 hectare size class represents all disturbances of 2000 hectares or greater.

Ten runs (Runs 1.2.1d-1.2.10d) were then analyzed in detail to explore the natural range of variability of forest conditions resulting from the natural disturbance assumptions in the absence of harvesting. Averages and the range of variation for indicator variables as measured in the last 100 years of simulation across the entire landscape are summarized in Table 4.2.

Table 4.2. Indicator variables (years 300-400) – growth and disturbance scenario (Runs 1.2.1d-1.2.10d).

		Total	THLB	NTHLB	Regime 1	Regime 2
Late Seral %	Min	13.5	14.1	6.7	0.0	21.5
	Average	**44.3**	**44.5**	**43.0**	**37.7**	**50.9**
	Max	72.8	76.2	93.3	89.5	76.0
Growing Stock	Min	166,020	138,920	14,410	0	159,210
	Average	**486,860**	**416,191**	**70,668**	**211,432**	**275,428**
	Max	718,550	623,060	127,790	432,640	377,070
Area in Patches 0-50 ha	Min	210				
	Average	**393**				
	Max	610				

Table 4.2 shows the area in small patches averages 393 hectares, but ranges from 210 to 610 hectares. The average percentage of late seral area is very similar in the THLB, NTHLB and the total landscape, reflecting the fact that these areas all share equal proportions of Regime 1 and Regime 2. However, the range of variation between the THLB and NTHLB is quite different, demonstrating how smaller areas can have much wider ranging conditions than larger areas. The total landscape, being the largest area under consideration, has the narrowest range of variation. Regime 1 and Regime 2 have different average percentage of late seral area, reflecting the different disturbance rates of each regime. The range of variation is also much wider in Regime 1, reflecting the more volatile rate of disturbance.

Growing stock development across the entire landscape is illustrated in Figures 4.4 to 4.6, and is compared to the growth-only growing stock developed in Section 3.1.1.

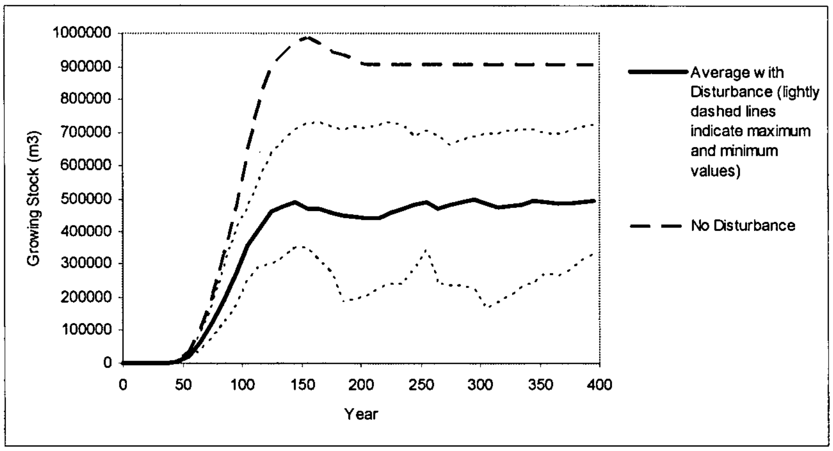


Figure 4.4. Growing stock - growth and disturbance scenario (Runs 1.2.1d-1.2.10d).

With disturbance, average growing stock levels at the end of simulations were 494,510 m^3, however the range of variation is wide, with growing stock in the last period ranging from 327,500 m^3 to 718,550 m^3. Growing stock development in Figures 4.5 and 4.6 reveals that the two disturbance regimes have not only different averages, but also different levels of variation.

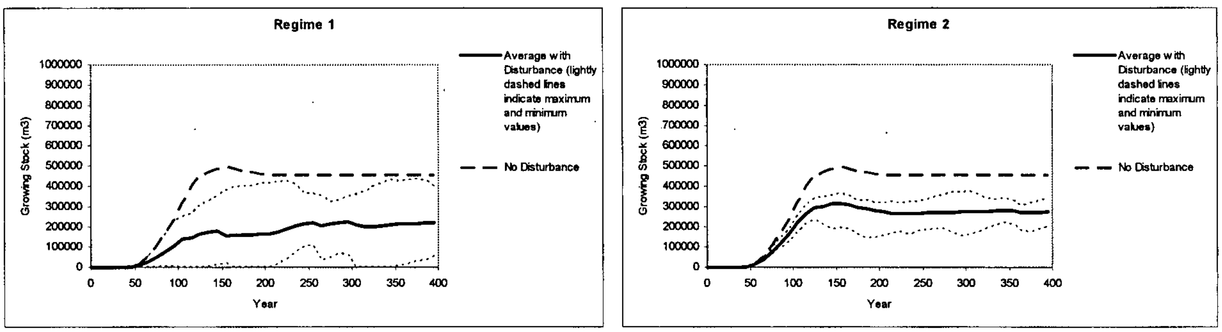


Figure 4.5. Growing stock in regimes - growth and disturbance scenario (Runs 1.2.1d-1.2.10d).

The lower disturbance rate in Regime 2 results in higher average amounts of growing stock in the final period (272,578 m^3) compared with Regime 1 (217,553 m^3). Regime 1 has a more volatile rate of disturbance, leading to the wide range of variation in growing stock, which has an upper bound that is similar to the upper bound in Regime 2 (actually slightly higher).

Growing stock development on the THLB and NTHLB is illustrated in Figure 4.6

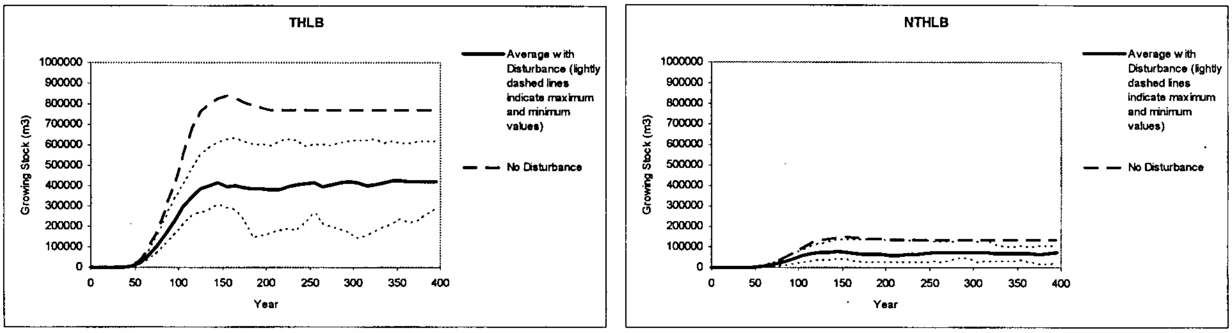


Figure 4.6. Growing Stock in the THLB and NTHLB - growth and disturbance scenario (Runs 1.2.1d-1.2.10d).

Because the NTHLB is small, it has less absolute variation in growing stock levels. However, the volatility of the growing stock is higher in the NTHLB when expressed as a percentage of the maximum possible growing stock, with a range that is 63% of the maximum, as compared with 43% of the maximum on the THLB.

4.1.3 Growth and Harvest

A starting point was then established for the harvesting scenarios, using a landscape condition resulting from 400 years of disturbance simulation as described in Section 3.1.2. This was assumed to represent the conditions resulting from the disturbance rates modeled. One run (Run 1.2.1d) was arbitrarily selected from the set of runs in Section 3.1.2, and the resulting stand ages were assigned to polygons. The seral stages reflecting these ages, and their associated patches (contiguous areas of the same seral stage), are illustrated in Figure 4.7. Most of the larger patches over 100 hectares in Figure 4.7 occur in Regime 1 because of its large disturbance event sizes.

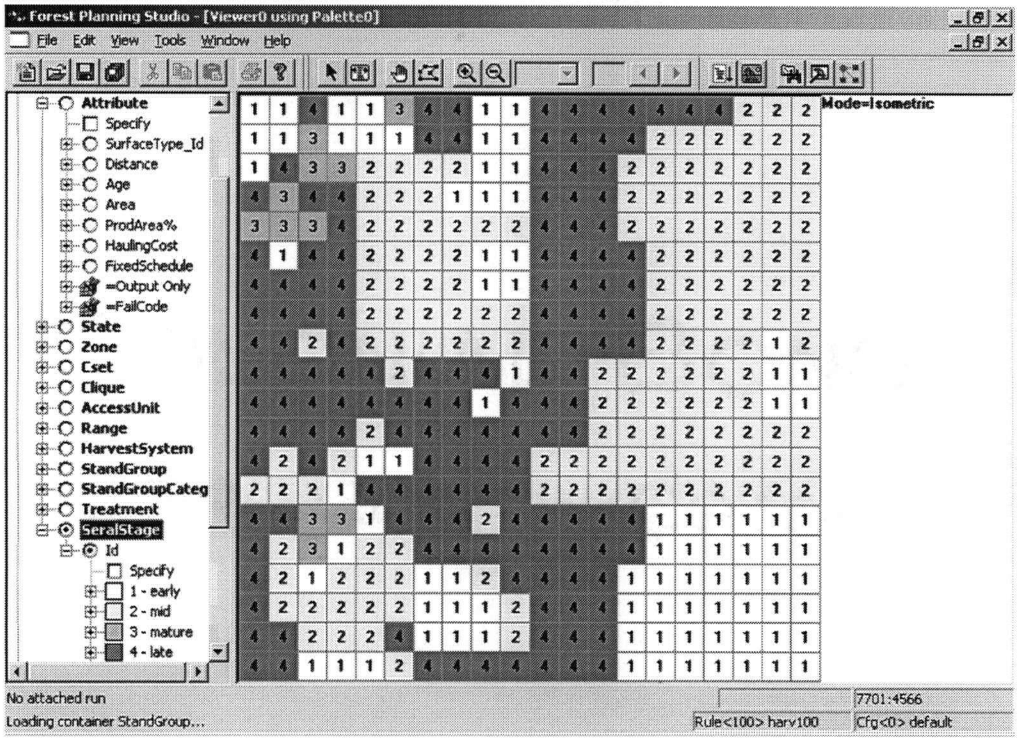


Figure 4.7. Starting seral stages for harvest scenarios. Numbers in each polygon refer to seral stage (legend on left).

A maximum harvest flow for this landscape (Run 1.3.1d) was then determined (no disturbance) and is illustrated in Figure 4.8. Timber availability, as determined by testing each period in the simulation as outlined in Section 3.3.2, is also shown in Figure 4.8.

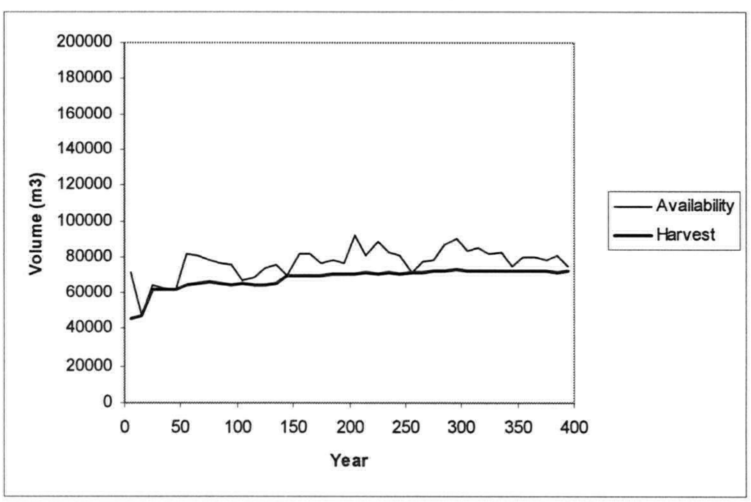


Figure 4.8. Harvest and availability - growth and harvest scenario (Run 1.3.1d and Runs 1.3.1a – 1.3.40a).

Harvesting in the first two decades is limited to approximately 45,000 m^3 per decade. As the age-class distribution becomes more balanced, and as stands are converted to higher yield managed stand types, the harvest volume increases through the first 150 years, up to a long-term sustainable harvest rate of approximately 71,000 m^3 per decade. The availability curve is equal or close to the harvest rate through much of the simulation in Figure 4.8, indicating that available timber is almost fully utilized. Harvest volumes taken from Regime 2 are initially higher than Regime 1, because the older stands there are harvested with a higher priority. However, as the age classes become more balanced, the volumes harvested from the two regimes are roughly equal, and at the end of the simulation average 33,205 m^3 per period in Regime 1 and 34,721 m^3 per period in Regime 2.

Figure 4.9 shows the state of the forest following 400 years of harvesting without disturbance using the harvest flow in Figure 4.8. A very different kind of forest has been created, with all stands in the THLB converted to managed stands, and late seral stage area completely eliminated. In contrast, the NTHLB has aged continuously in the absence of harvesting and disturbance, and now consists of a single patch of late-seral forest.

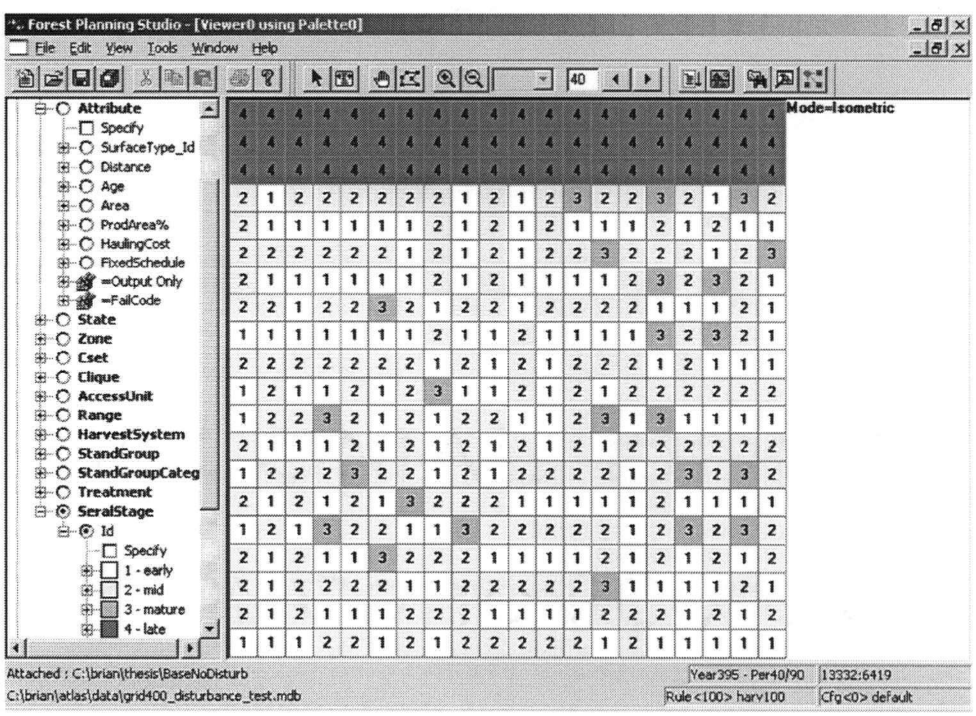


Figure 4.9. Seral stages - growth and harvest scenario (Run 1.3.1d). Numbers in each polygon refer to seral stage (Legend on Left).

Figure 4.10 further demonstrates the changes in percentage of late seral area. While the total percent area in late seral stands drops to 16%, the THLB and NTHLB, which initially reflect similar amounts of older age-classes, diverge to 0% and 100%, respectively.

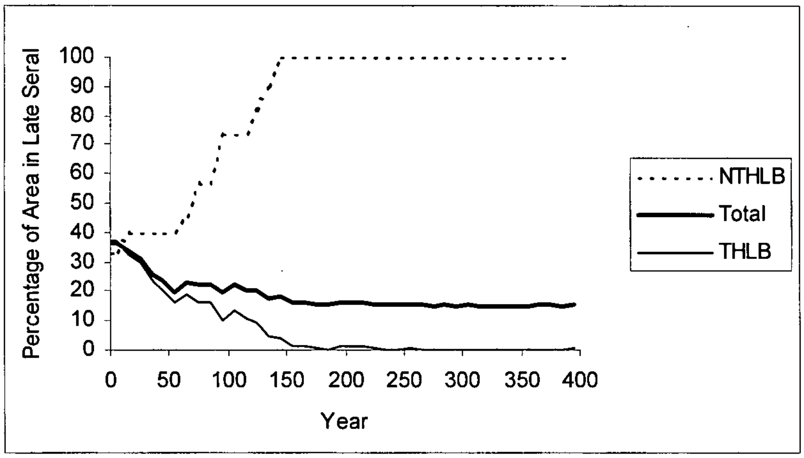


Figure 4.10. Late seral percents - growth and harvest scenario (Run 1.3.1d).

Figure 4.11 shows the growing stock trajectory for Run 1.3.1d. Growing stock in the THLB is drawn down over the first 150 years of the simulation from 382,170 m^3 to approximately 240,000 m^3. On the NTHLB, growing stock rises steadily during this time from 61,110 m^3 to approximately 136,000 m^3, reflecting the continuous aging of stands.

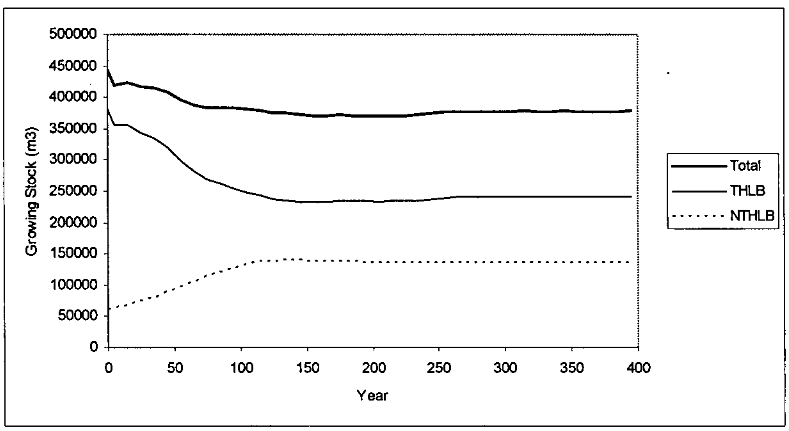


Figure 4.11 Growing stock - growth and harvest scenario (Run 1.3.1d).

4.1.4 Growth, Disturbance and Harvest

Harvesting was next simulated in combination with explicit disturbance simulation. To determine a sustainable rate of harvest, harvest targets were tested systematically until a sustainable harvest was found using the methods outlined in Section 3.3.3.

A sustainable harvest target within the risk tolerance (0.1) was achieved at 24,832 m^3 per period, as demonstrated by the proportions of failed runs and corresponding estimate of risk shown in Figure 4.12.

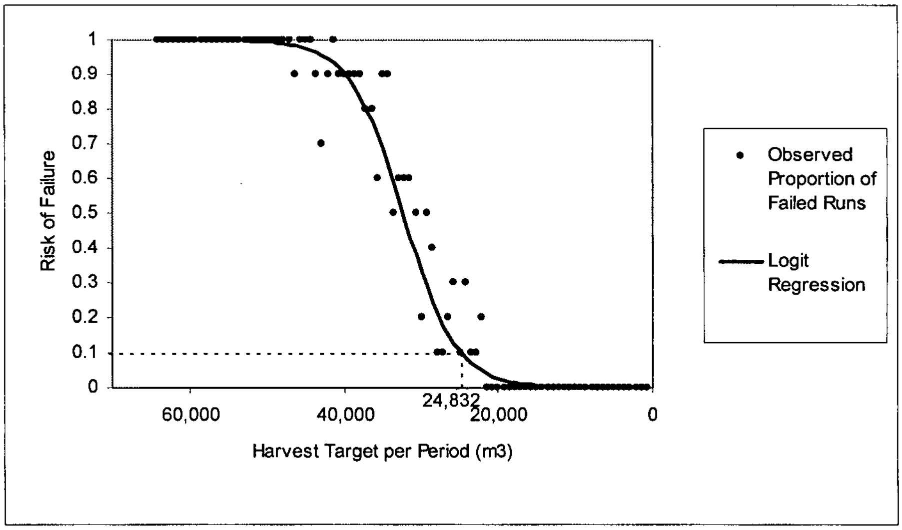


Figure 4.12. Estimated risk for harvest targets - growth, disturbance and harvest scenario (Runs 1.4.1h to 1.4.900h).

Figure 4.13 demonstrates the average harvest volumes obtained from each regime when disturbance is explicitly simulated, in comparison with the long run sustainable harvest volumes obtained when disturbance is not simulated.

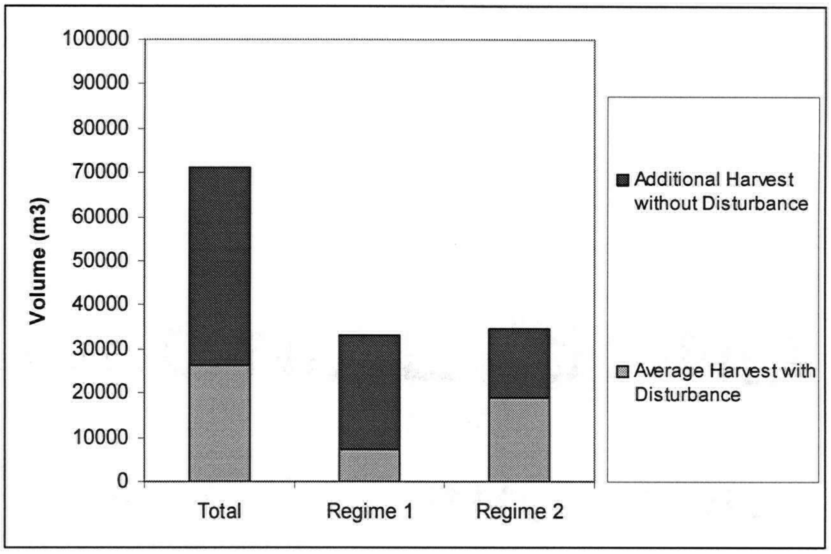


Figure 4.13. Harvest flows with and without disturbance.

With disturbance, volume harvested from Regime 1 averages 7,315 m^3 per period, and volume harvested from Regime 2 averages 18,827 m^3 per period. The difference in harvest with and without disturbance, can be thought of as one way of buffering against the impacts of natural disturbance. The buffer required in Regime 1, with its higher and more volatile rate of disturbance is greater than the buffer required in Regime 2. The harvest rate and availability is shown in Figure 4.14, for one run with disturbance (Run 1.4.1d).

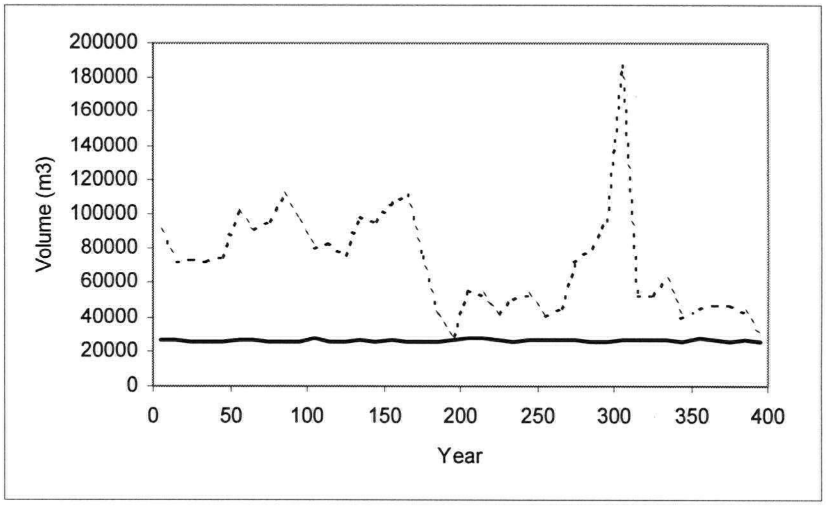


Figure 4.14. Harvest and availability (dashed line) (Run 1.4.1d) - growth, disturbance and harvest scenario.

Figure 4.14 demonstrates that harvesting is constrained to a level that is approximately equal to the minimum availability encountered through time. Large spikes in availability occur, with one peak over 180,000 m^3.

Figure 4.15 shows the area disturbed for this same run, and demonstrates that the peaks and subsequent drops in availability in Figure 4.14 correspond to periods where large amounts of disturbance create excess amounts of salvageable timber.

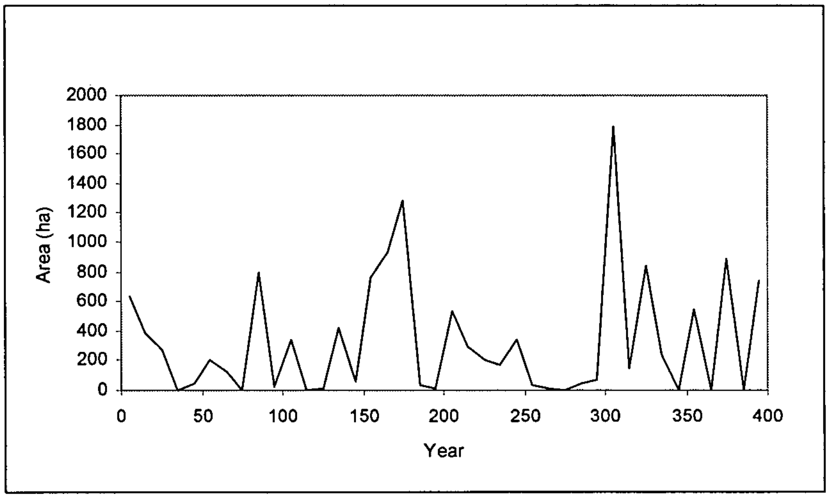


Figure 4.15. Area disturbed (Run 1.4.1d) - growth, disturbance and harvest scenario.

Figure 4.16 confirms that the amount of disturbance in Regime 1 is higher than Regime 2, and that it is more volatile.

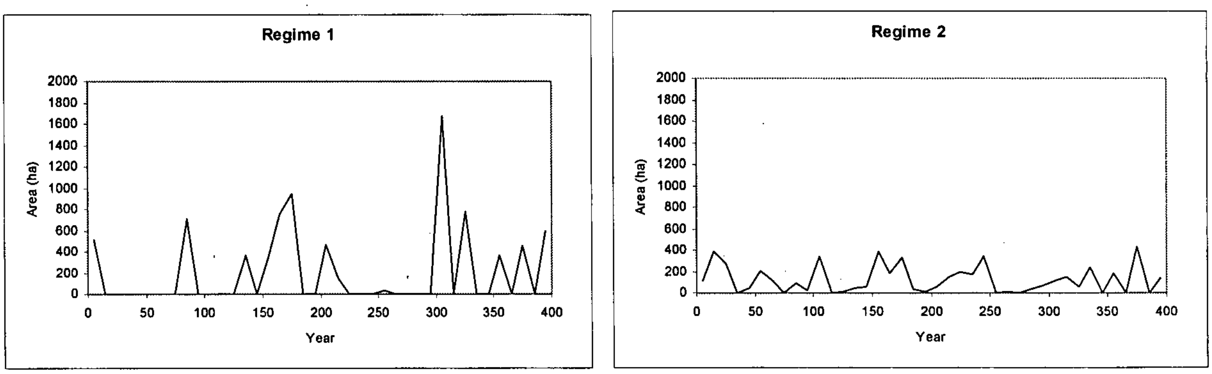


Figure 4.16. Area disturbed in regimes (Run 1.4.1d) - growth, disturbance and harvest scenario.

Figure 4.17 shows the amount of volume harvested and the amount of disturbed volume that is salvaged. Some areas are not salvaged because they are either below the minimum harvest age, are not in the THLB, or their harvest would exceed the volume target for the period. During periods of high disturbance, harvest volumes can consist entirely of salvage wood. Although harvesting in this example is limited to the sustainable even-flow harvest target, harvest volumes could in fact be boosted in periods with excess salvage volume to levels that utilize all disturbed stands.

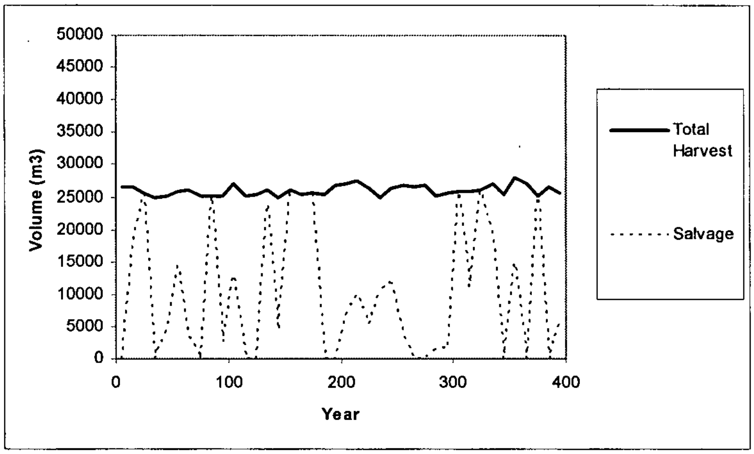


Figure 4.17. Total harvest and salvage (Run 1.4.1d) - growth, disturbance and harvest scenario.

Timber availability was then examined by performing 30 tests of availability in each period as described in Section 3.3.2. Figure 4.18 shows the average, maximum and minimum values for timber availability using the 24,832 m^3 per year harvest target. There is no increasing trend in availability beyond year 100, indicating that there is likely no potential for increasing the harvest rate during later periods. However, availability averages 81,991 m^3, with maximum values of over 200,000 m^3.

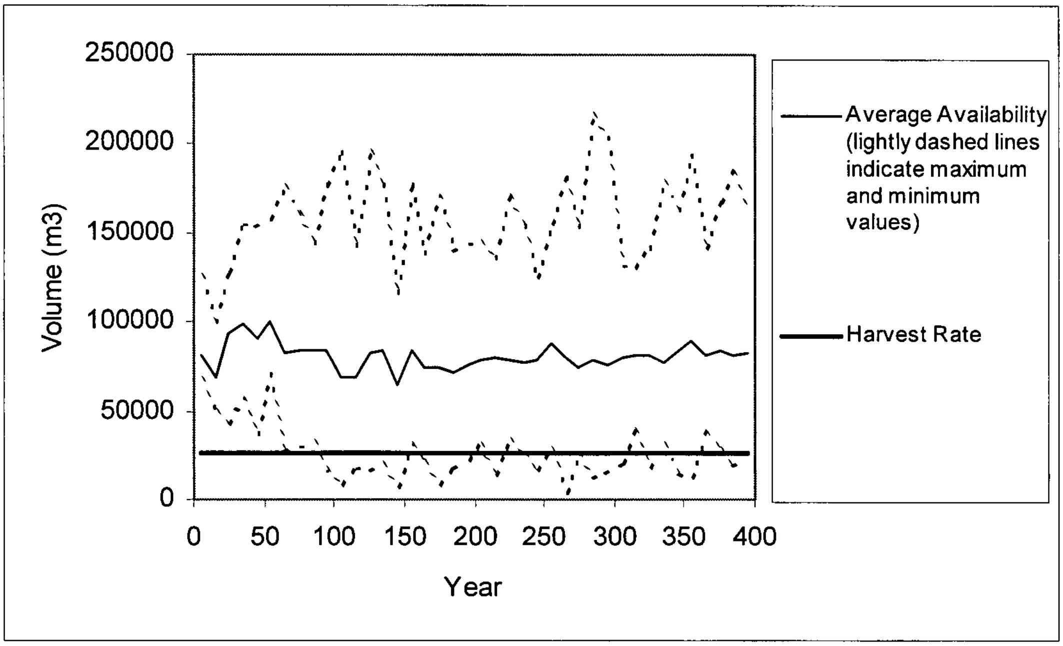


Figure 4.18. Harvest and availability - growth, disturbance and harvest scenario (Runs 1.4.1a-1.4.1200a).

The excess availability in Figure 4.18 can be thought of as another measure of a buffer on the landscape that has the ability to absorb variation in disturbance activity without impacting the harvest rate. During some periods where large amounts of disturbance occur, the buffer drops to zero, and availability is equal to the harvest target, or occasionally less than the harvest target. Figure 4.18 shows some periods with minimum availability levels that are below the harvest target, though these shortfalls are infrequent enough to be within the risk tolerance or modest enough to be within the shortfall tolerance. During the last 100 years of the simulations, availability averages 55,848 m^3, which is approximately 2.1 times the harvest target. The variability of the buffer reflects the variability in disturbance rates, and harvesting is constrained to levels that are approximately equal to the minimum levels of availability (though this depends on risk tolerance).

Figures 4.19 and 4.20 show the average harvest rate and availability of timber within the individual disturbance regimes. Regime 2 provides an average of 72% of the total harvest measured over the last 100 years.

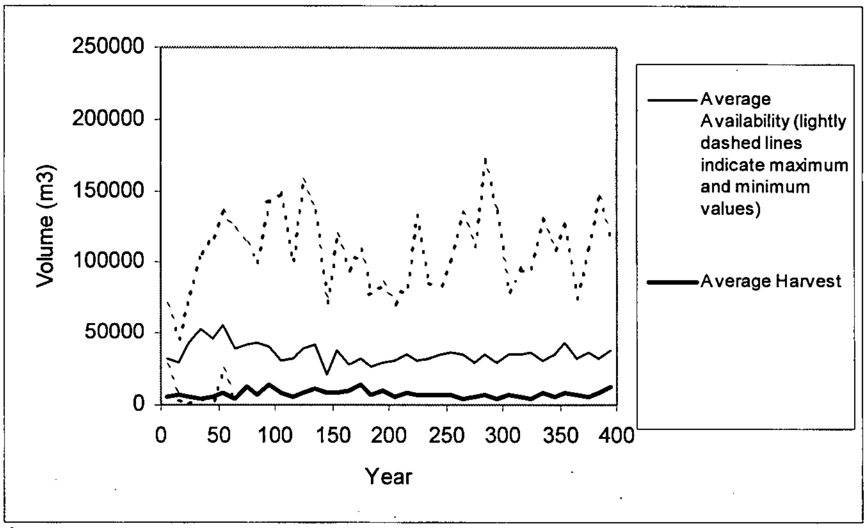


Figure 4.19. Harvest and availability in Regime 1 - growth, disturbance and harvest scenario (Runs 1.4.1a-1.4.1200a).

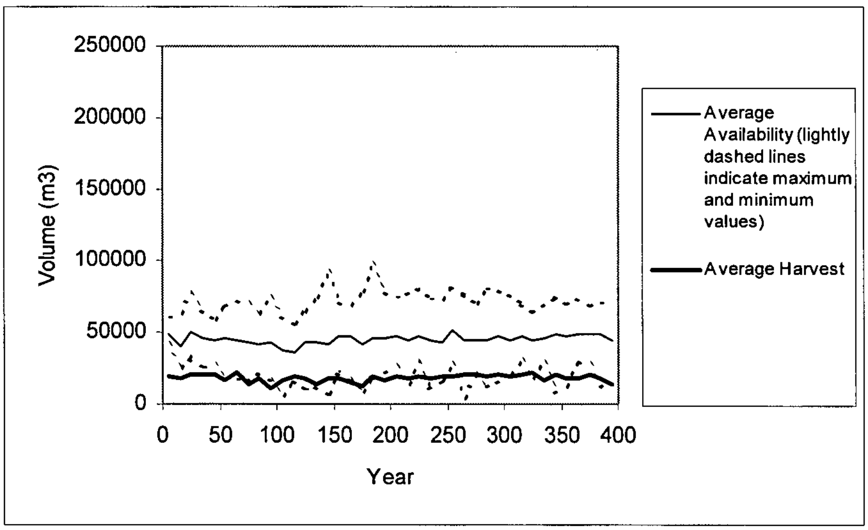


Figure 4.20. Harvest and Availability in Regime 2 - growth, disturbance and harvest scenario (Runs 1.4.1a-1.4.1200a).

Average availability is higher in Regime 2, however when expressed in terms of the harvest, it is only 1.5 times the harvest level, compared with 3.8 times the harvest level in Regime 1. The range of variation in availability in Regime 2 over the simulations is approximately 5000 m^3 to 100,000 m^3. Regime 1 has availability that is erratic, reflecting the erratic pattern of disturbance, and after year 65, shows a range of variation between 0 and over 150,000 m^3 (Figure 4.19).

Figures 4.21 through 4.23 show the growing stock dynamics. Average growing stock levels are similar to those maintained by harvesting without disturbance, but are highly variable, ranging from less than 200,000 m^3 to over 600,000 m^3.

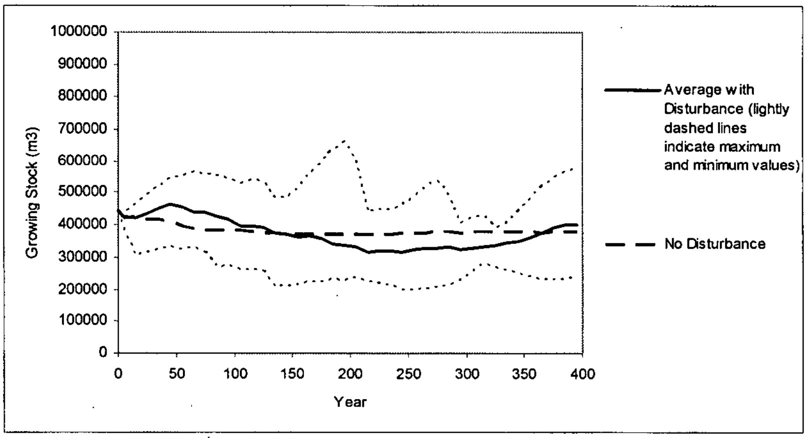


Figure 4.21. Growing stock - growth, disturbance and harvest scenario (Runs 1.4.1d-1.4.10d).

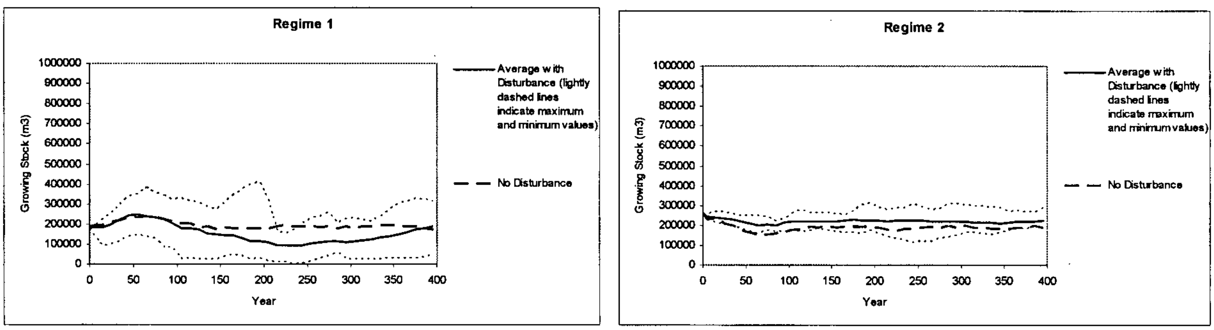


Figure 4.22. Growing stock in regimes - growth, disturbance and harvest scenario(Runs 1.4.1d-1.4.10d).

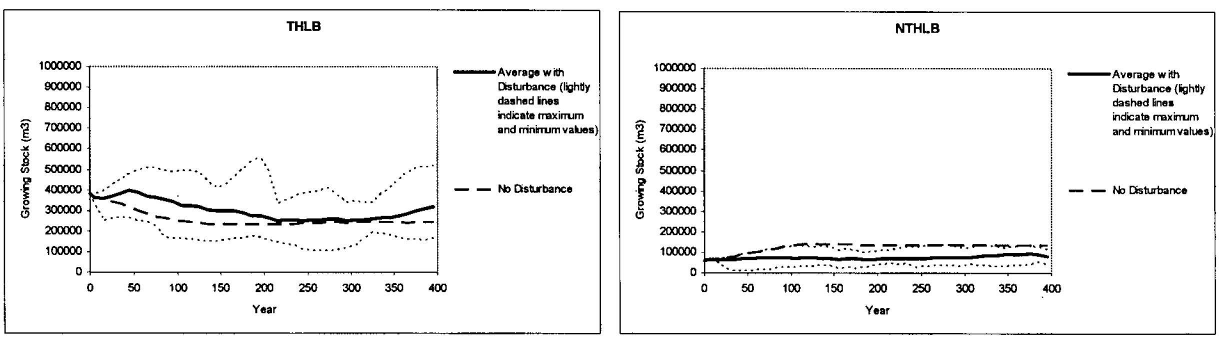


Figure 4.23. Growing stock in the THLB and NTHLB - growth, disturbance and harvest scenario (Runs 1.4.1d-1.4.10d).

Figure 4.22 shows that variation in growing stock is much higher in Regime 1 than Regime 2. Figure 4.23 shows that on the THLB the average growing stock is similar to the growing stock produced by harvesting without disturbance, though the range of variation is wide. The NTHLB shows less absolute variation because it is a small area.

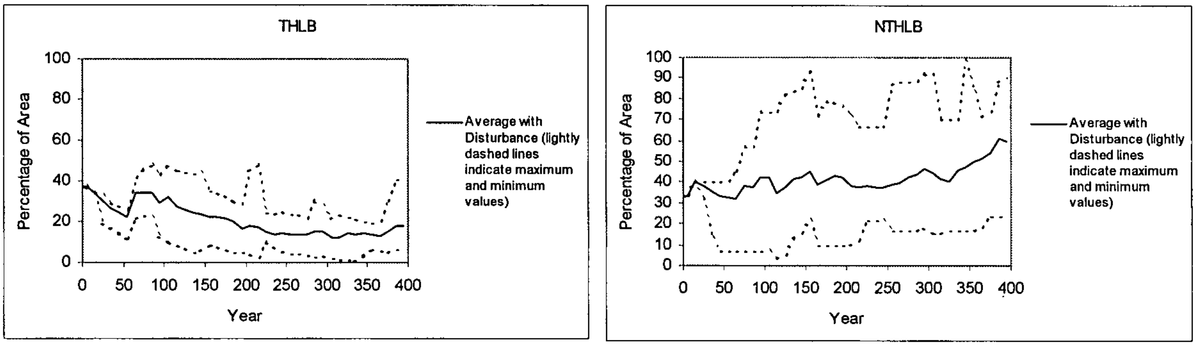


Figure 4.24. Late seral in the NTHLB and THLB - growth, disturbance and harvest scenario (Runs 1.4.1d-1.4.10d).

Figure 4.24 shows that the percentage of area in late seral stands on the NTHLB can be highly erratic, ranging from less than 10% to nearly 100%. Significant amounts of late seral stands also remain on the THLB, declining to an average of approximately 14.4% after year 300. A wide range of variation still exists, with minimum values of less than 5% and peaks of over 40%. A surge in late seral stands occurs during years 75 to 85 (when several large areas age into the late seral category). This is an artifact of the initial age-class distribution at the start of the simulation.

Figure 4.25 graphs the dynamics of small patch area across the landscape. As harvesting is introduced, the area in small patches increases. However, disturbance events soon form larger patches, reducing the small patch area to under 1000 hectares.

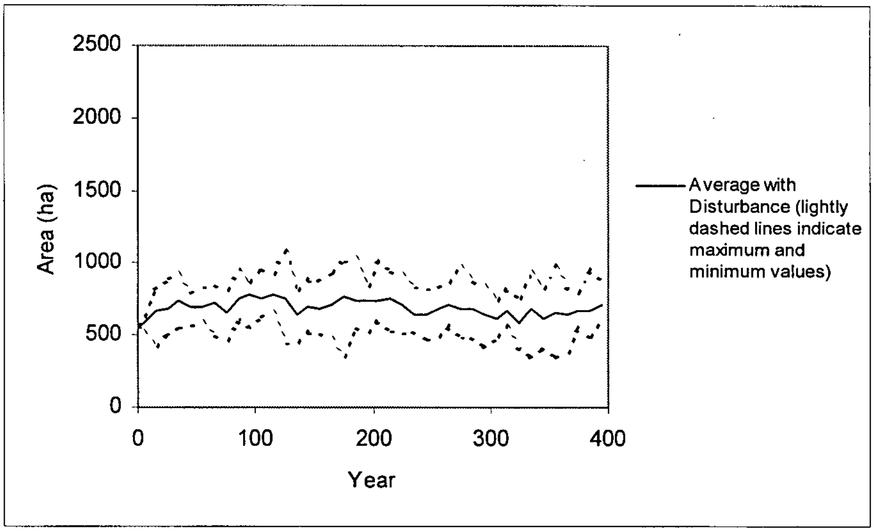


Figure 4.25. Area in small patches - growth, disturbance and harvest scenario (Runs 1.4.1d-1.4.10d).

Table 4.3 summarizes mean, maximum and minimum values observed for indicator variables in the last 100 years of the harvest and disturbance simulations.

Table 4.3. Landscape statistics (years 300-400) – growth, disturbance and harvest scenario (Runs 1.4.1d-1.4.10d).

		Total	THLB	NTHLB	Regime 1	Regime 2
Late Seral %	Min	6.5	0.9	15.0	0.0	7.5
	Average	**19.7**	**14.4**	**49.5**	**14.9**	**24.5**
	Max	38.3	40.9	98.3	54.0	40.5
Growing Stock	Min	230,010	131,730	29,400	22,700	155,460
	Average	**362,948**	**277,539**	**85,409**	**146,627**	**216,321**
	Max	578,660	516,060	133,200	328,070	302,790
Area in Patches 0-50 ha	Min	350				
	Average	**649**				
	Max	970				

Comparing Table 4.3 with Table 4.2 (p. 37), the introduction of harvesting has decreased the amount of late seral stands in all areas except the NTHLB. Average growing stock also decreased with the introduction of harvesting, while the area in small patches increased.

4.1.5 The Effect of Salvage Logging on Harvest Rates

To determine the effect of salvage harvesting, salvaging was turned off in the model, and the process of determining a sustainable harvest target was repeated, as shown in Figure 4.26.

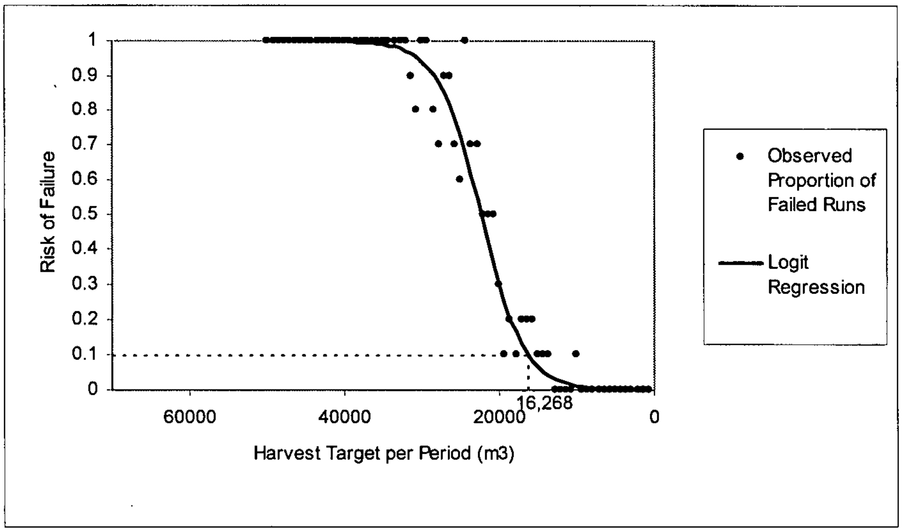


Figure 4.26. Estimated risk for harvest targets – no salvage scenario(Runs 1.5.1h-1.5.700h).

Using Figure 4.26 to estimate the harvest target with a 0.1 risk of failure results in a harvest target of 16,268 m^3 per period, which is approximately 66% of the harvest target that could be sustained with salvaging.

In the current model, disturbed stands are only salvaged until the harvest target for the period is met, potentially leaving large areas of disturbed and merchantable timber under-utilized. More salvage volume could be utilized by manually raising the harvest target during peak disturbance periods on individual runs. This would be extremely time consuming though, as the harvest target in each period would need to be carefully determined to use only the excess salvage stands and not the undisturbed stands. Enabling this to occur automatically within the model would require re-programming the harvest-scheduling simulator.

4.1.6 Sensitivity of the Harvest Rate to Simulation Length

A variety of time-spans were explored by truncating the harvest and disturbance simulations. Sustainable harvest rates were then re-estimated using the proportion of failed runs. The results for time-spans ranging from 20 to 400 years are shown in Figure 4.27.

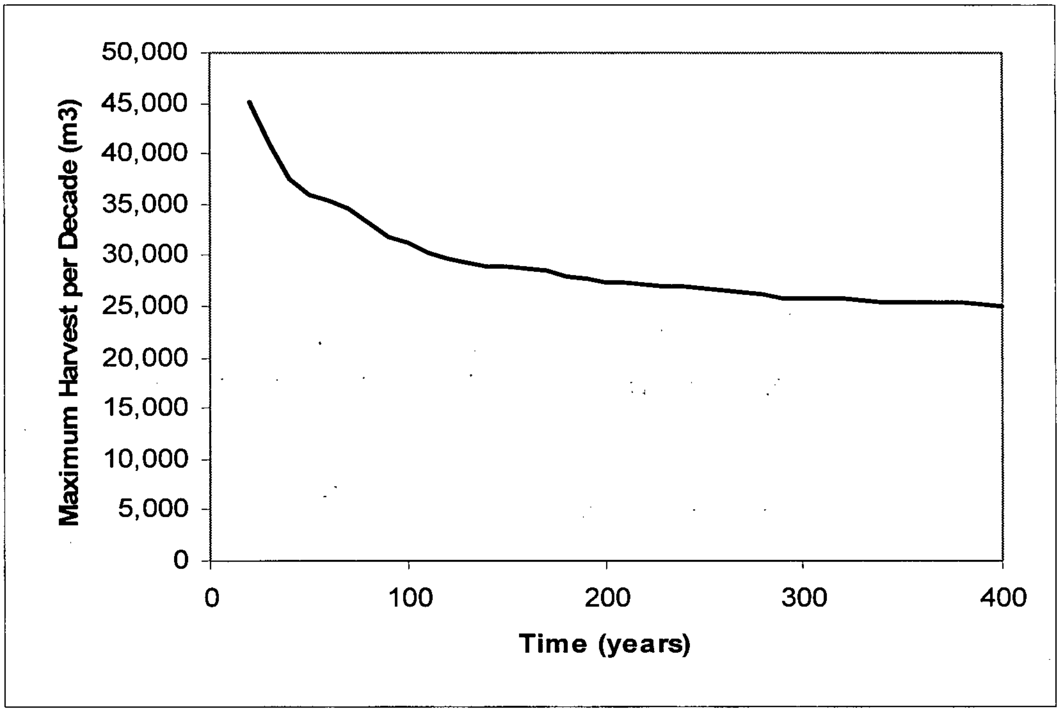


Figure 4.27. Sensitivity of the harvest rate to simulation length – growth, disturbance and harvest scenario (Runs 1.4.1h to 1.4.900h).

Figure 4.27 shows that the sustainable harvest rate can be highly sensitive to time, particularly for very short time-spans. When only twenty years are simulated, the sustainable rate of harvest is approximately 45,000 m^3 per decade. However, harvest levels from very short simulation lengths are mainly a reflection of the starting conditions of the forest, rather than long-term forest productivity. Sustainable harvest volumes drop quickly with longer simulation lengths, to 36,000 m^3 per decade over 50 years, 31,000 m^3 over 100 years and 27,000 m^3 over 200 years. As simulation length increases, the probability of at least one large disturbance period causing a major disruption increases. After 200 years, the sustainable harvest rate is only gradually declining with increased simulation length, suggesting that these long-term harvest targets reflect most of the major disturbance events.

4.1.7 Sensitivity of the Harvest Rate to Shortfall Tolerance

Sensitivity of the harvest rate to the shortfall tolerance was tested. Previous scenarios require a harvest in any one period to achieve 90% of the harvest target, otherwise a shortfall is recorded and the run is deemed to have failed. Harvest rates were recalculated using a range of shortfalls tolerances from only 50% of the harvest target up to 100% (Figure 4.28).

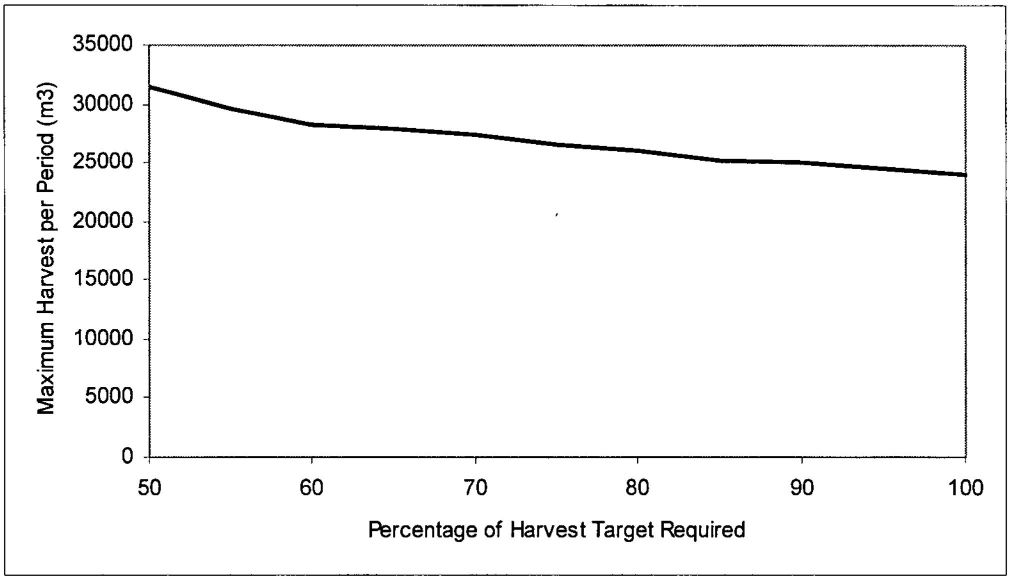


Figure 4.28. Sensitivity of the harvest rate to shortfall tolerance - growth, disturbance and harvest scenario (Runs 1.4.1h to 1.4.900h).
(Note that the scale on the percentage-axis starts at 50%.)

As Figure 4.28 shows, when the minimum harvest is set to 100% of the harvest target, the maximum sustainable harvest drops to 24,090 m^3 per decade. As the tolerance is relaxed, the harvest target can rise to approximately 31,000 m^3 per decade when a 50% shortfall is permitted.

4.1.8 Sensitivity of the Harvest Rate to Variation in Event Occurrence

Sensitivity of the harvest rate to the over-dispersion parameter was tested, using the original shortfall tolerance (0.9) and risk tolerance (0.1) from Section 4.1.4. Harvest rates for a range of α values are shown in Figure 4.29.

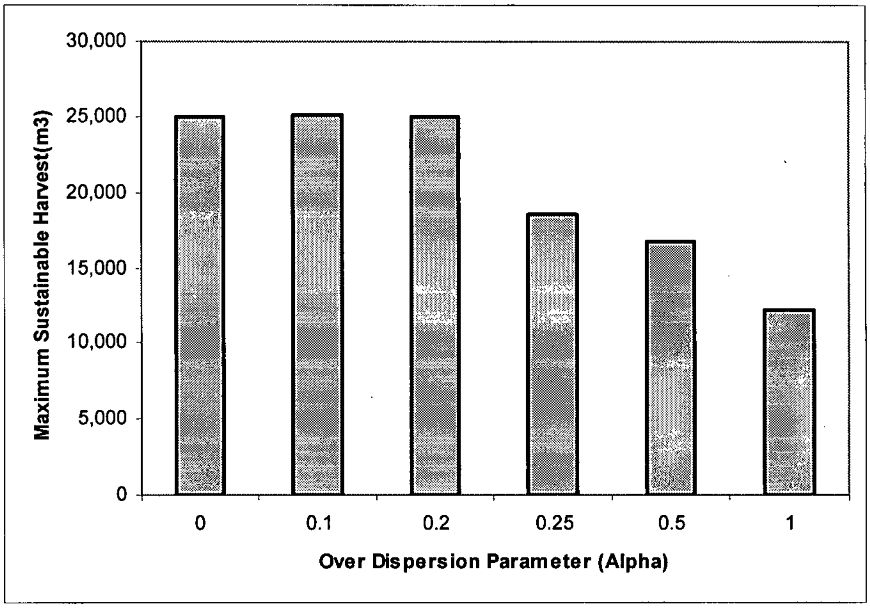


Figure 4.29. Sensitivity of the harvest rate to the over-dispersion parameter (Runs 1.4.1h to 1.4.900h and Runs 1.6.1h to 1.10.700h).

Figure 4.29 demonstrates that the over-dispersion parameter has virtually no effect at values below 0.2, however, α values of 0.25 to 1.0 produced much lower estimates of sustainable harvest rates. Increased α values create more variability in the number of disturbance events per period. Although the mean number of events remains the same, a high α value may produce peak years with much higher rates of disturbance. This is demonstrated in Figure 4.30 which shows the expected frequency of events per period from Regime 2 using two values for α (recall that the mean number of events is 2 per period). When an α value of 0.1 is used, zero events happen with a frequency of 0.16 and 6 events happen with a frequency of 0.017. When α is increased to 0.5 the mean number of events remains at 2, though 0 events now happen with a greater frequency of 0.25, and the frequency of periods when 6 events happen is also increased to 0.027.

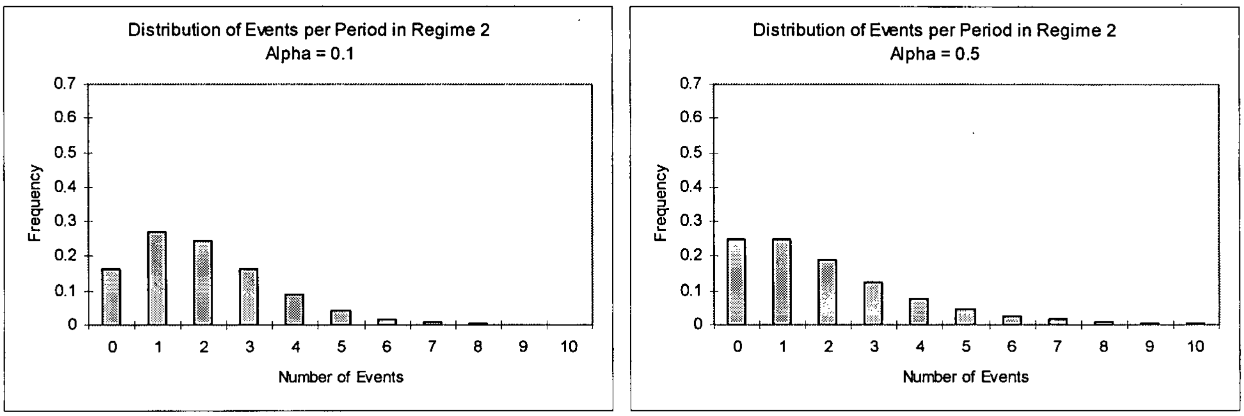


Figure 4.30. Frequency of Events per Period in Regime 2 Using Two Over-Dispersion Parameters.

4.1.9 Interaction Between Regimes

The interaction between the two disturbance regimes was examined by simulating disturbance and harvesting on each regime in isolation. Estimates of sustainable harvest targets using a shortfall tolerance of 90% and a risk level of 0.1 are shown in Figure 4.31.

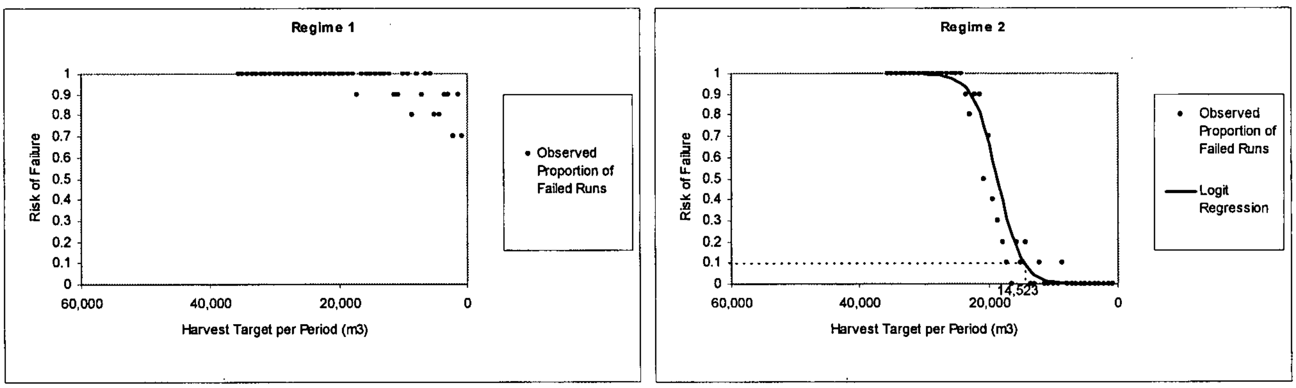


Figure 4.31. Estimated risk for harvest targets – regimes simulated individually (Runs 1.11.1h to 1.12.700h).

Even when very low rates of harvest in Regime 1 were tested, periods occur where catastrophic disturbance events create conditions where the targets cannot be met. The lowest target tested was approximately 700 m^3 per period, which is less than the volume obtainable from one polygon at the minimum harvest age. Even with this minimum harvest target, seven out of the ten simulations failed to sustain this volume in every period. Regime 2, with its lower and less volatile disturbance rate has a sustainable harvest rate of approximately 14,523 m^3 per period.

When these estimates are summed, they add up to much less than the 24,831 m^3 per period determined to be sustainable in Section 4.1.4. This demonstrates the synergy between the two parts of the landscape in producing a sustainable harvest target that is greater than the sum of the parts. When timber is available in both regimes, the harvest scheduler can select stands from either Regime based on the scheduling priority. When large disturbance events hit, which most often occurs in Regime 1, harvesting can shift to the high priority salvage stands, taking advantage of the short-term availability, while allowing growing stock to accumulate in Regime 2. During a subsequent crash in availability in Regime 1, Regime 2 then has a greater capacity to provide timber supply while the growing stock recovers in Regime 1.

4.1.10 Sample Size and Regression Estimation

The regression estimate of risk used to determine sustainable harvest rates was re-evaluated by conducting a large batch of runs, using a high-speed processor that became available during the later stages of this project. The harvesting and disturbance scenario was re-tested by increasing the sample size at each harvest target from ten runs to fifty runs. The failure pattern and regression using 50 runs per harvest target is presented in Figure 4.32.

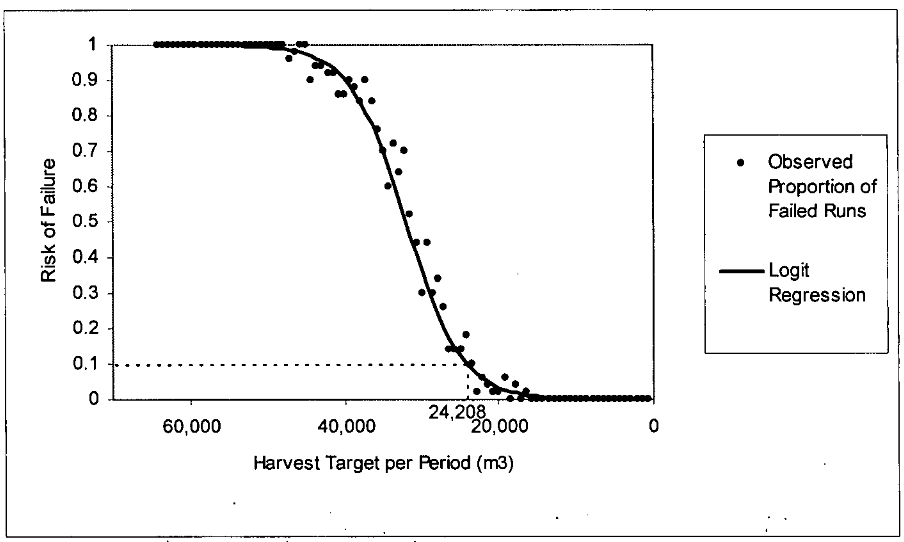


Figure 4.32. Estimated risk for harvest targets – 50 runs per harvest target (Runs 1.13.1h to 1.13.4500h).

Figure 4.32 demonstrates the excellent fit between the failure pattern and the logistic model used for the regression estimate of risk. Regression estimates using 50 runs per target and 10 runs per target are plotted in Figure 4.33.

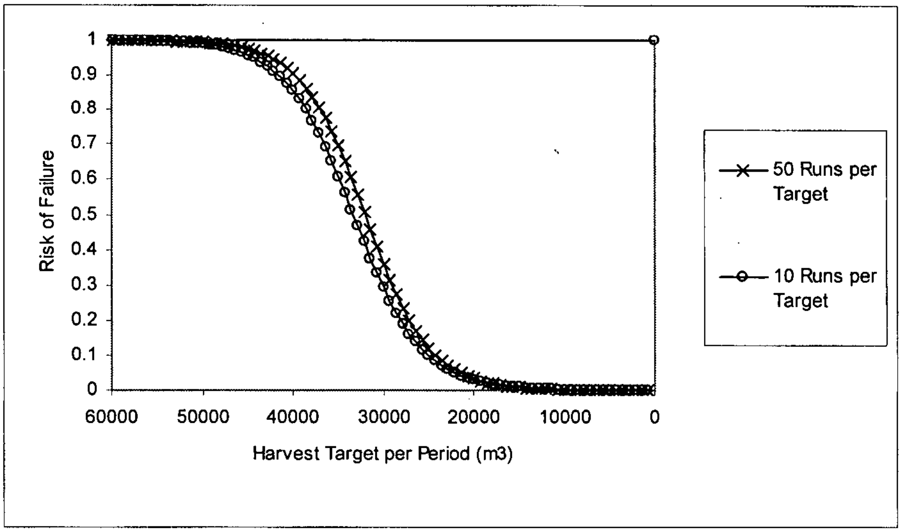


Figure 4.33. Estimated risk for harvest targets – comparison of 10 runs per harvest target and 50 runs per harvest target.

Figure 4.33 confirms that the estimate of the relationship from only ten runs per harvest target is very similar to that returned with the larger sample size. The estimate of the harvest target that would have a risk level of 0.1 is 24,208 m^3 per period using 50 samples per harvest target. The estimated harvest using only 10 samples per harvest target is slightly higher (24,832 m^3), but is within 2.6% of the 50-run estimate.

Statistical evaluations of the goodness-of-fit and confidence intervals around these regressions are complex and beyond the scope of this thesis. However, Figure 4.32 (and Figures 4.12, 4.26 and 4.31) clearly demonstrate the regression model fits the data well, has the expected shape, and does not produce predicted values that are outside the possible range of values (1,0). The regression that uses only 10 samples per harvest target will have a wider confidence interval than the one that uses 50 samples.

4.2 TFL 48 Block 4 Scenarios

The model was next applied to TFL 48 Block 4 to demonstrate its application to a larger scale harvest scheduling problem. In addition to analyses on harvest rates and landscape statistics, an economic analysis of the impacts of both natural disturbance and suppression is included. A base case scenario was initially run which assumed no disturbance aside from harvesting, to present the most optimistic estimate of sustainable rates of harvesting against which other scenarios could be compared. Four disturbance scenarios were then run. First, historical rates of disturbance were simulated without harvesting to estimate the 'natural range of variation' (NRV) in landscape statistics. Historical rates of disturbance were also simulated alongside harvesting, and the reduction in harvest required for sustainability provided an estimate of the cost of disturbance. Next, harvesting was simulated alongside disturbance events that are suppressed to 30% of their natural size, to estimate the effects and value of suppressing disturbance. Finally, harvesting was simulated alongside suppressed disturbance where some of the largest events were assumed to be beyond human control. This allowed the effects and cost of these largest events to be estimated, and perhaps provides the most realistic picture of the effects and value of suppression.

4.2.1 Growth and Harvest

The maximum sustainable harvest and availability without disturbance is shown in Figure 4.34.

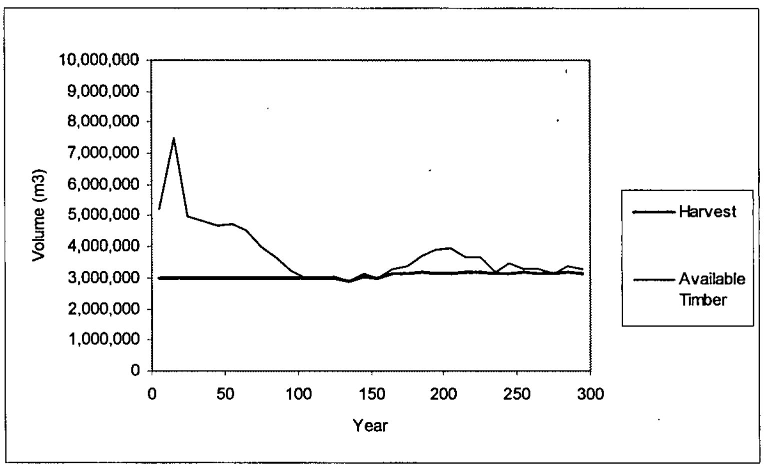


Figure 4.34. Harvest and availability – growth and harvest scenario (Run 2.1.1d and Runs 2.1.1a – 2.1.30a).

As shown in Figure 4.34, harvesting without disturbance can be maintained at 2,980,000 m^3 per period until year 140, when a small rise to 3,160,000 m^3 per period is possible. After an initial peak in the second period, availability declines steadily over the first 100 years until available timber is drawn down to levels that are close to the harvest rate, averaging 1.09 times the harvest target after year 150. The dynamics of landscape variables are shown in Figures 4.35 through 4.37.

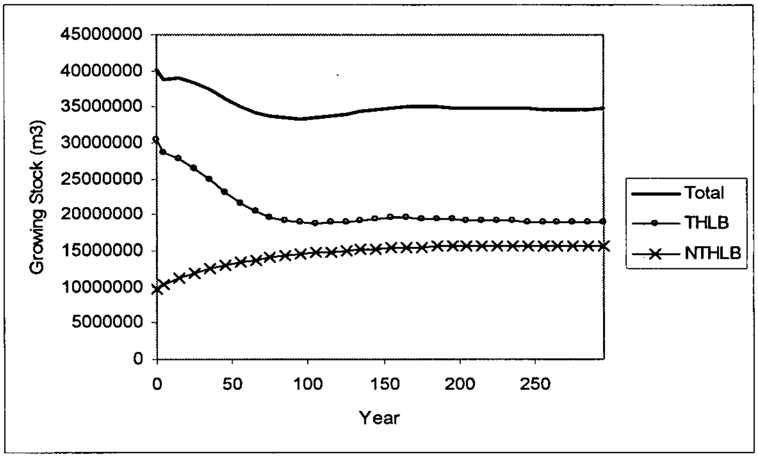


Figure 4.35. Growing stock – growth and harvest scenario (Run 2.1.1d).

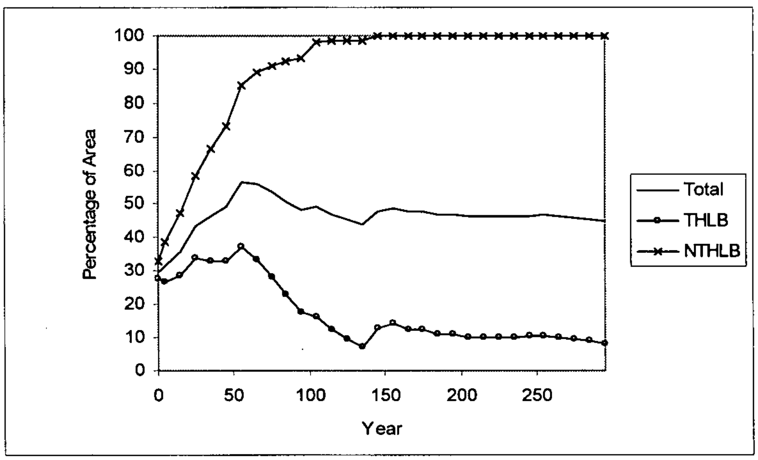


Figure 4.36. Late seral – growth and harvest scenario (Run 2.1.1d).

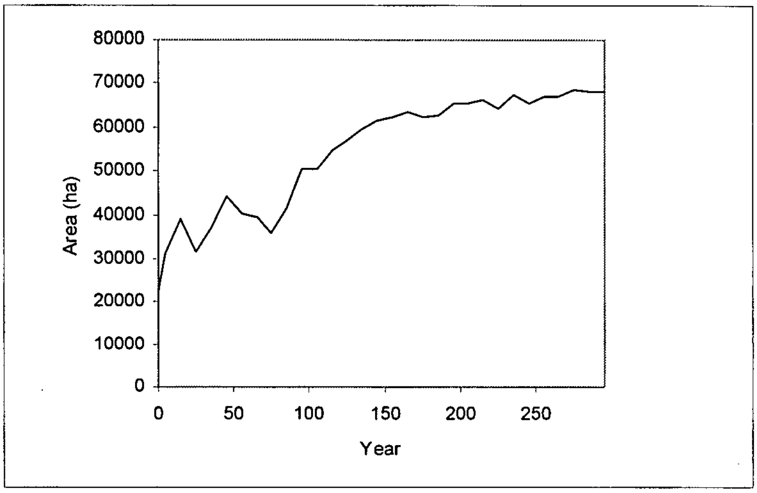


Figure 4.37. Area in small patches – growth and harvest scenario (Run 2.1.1d).

Figure 4.35 confirms that harvesting without disturbance draws down the growing stock on the THLB, while allowing it to grow unrestricted on the NTHLB. The aggressive rate of harvest that can be achieved without disturbance draws down the percentage of late seral area from 28% to 10% on the THLB, as shown in Figure 4.36. On the other hand, the NTHLB consists entirely of late seral stands by the end of the simulation. Figure 4.37 shows that the dispersed harvesting pattern increases the area in small patches across the landscape from 23,000 ha to approximately 67,000 ha.

Estimates of total revenue and cost are shown in Figure 4.38, which results in total net revenue of approximately $79 million per decade.

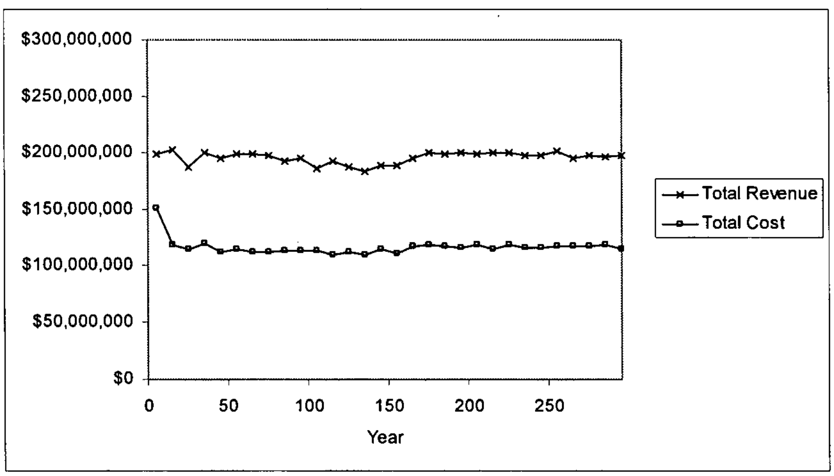


Figure 4.38. Costs and revenues – growth and harvest scenario (Run 2.1.1d).

Figure 4.38 demonstrates relatively stable revenue and costs throughout the simulation, yielding average profits of $25.73/ m^3. Individual unit cost categories are shown in Figure 4.39.

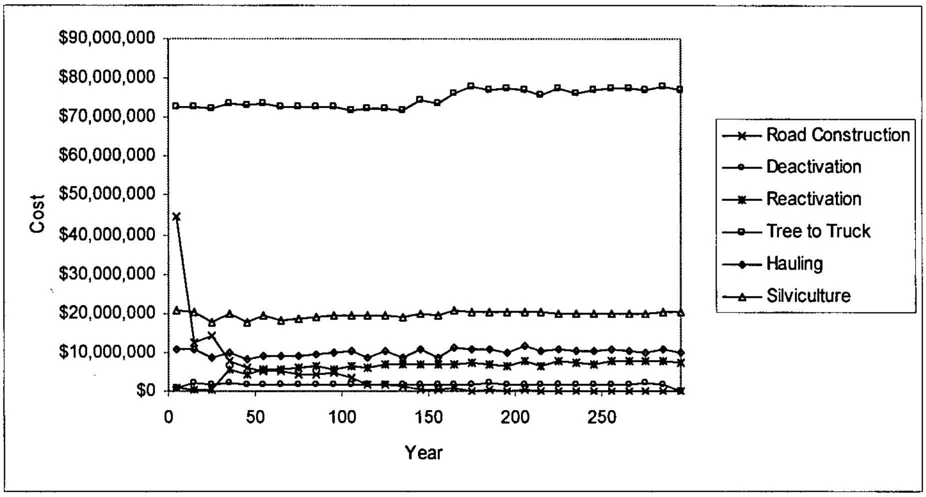


Figure 4.39. Cost details – growth and harvest scenario (Run 2.1.1d).

Throughout the simulation, tree-to-truck costs are the highest cost component. Road construction costs are initially the second largest component. During the first period, large amounts of road need to be constructed. This cost soon drops as access is established. Silviculture then becomes the second largest cost, followed by hauling, re-activation, construction and deactivation. After year 120, the road network is largely established, and road construction costs become the lowest cost. The net present value (NPV) of 300 years of timber harvesting using various discount rates is shown in Figure 4.40.

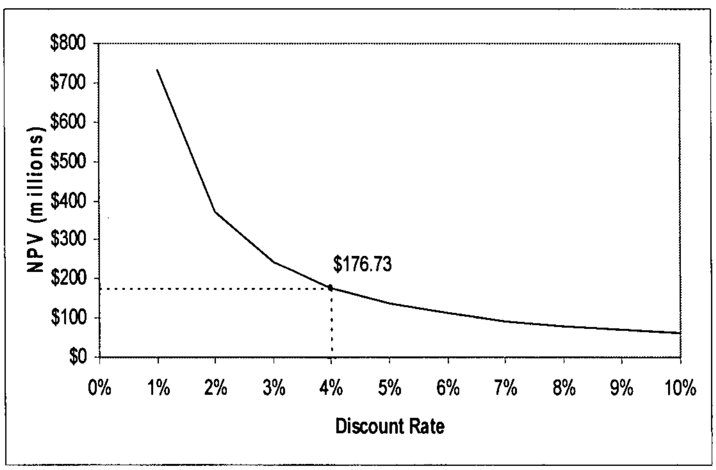


Figure 4.40. Net present value – growth and harvest scenario (Run 2.1.1d).

Assuming a 4% discount rate, the NPV is $176,725,068. As discussed in Section 3, discounting assigns value with bias towards profits earned today and costs incurred tomorrow, and represents what a firm might be willing to pay for this piece of land for 300 years of exclusive timber harvesting. Taxes and profit required by the firm are not included. Discount rates used by private sector purchasers could also be much higher than 4%, placing more bias on short-term profitability. However, discounting here is simply being used to compare relative net present value between scenarios, which would likely be the same across a range of discount rates and cost assumptions.

4.2.2 Growth and Historical Disturbance

Historical natural disturbance was then simulated on Block 4 without harvesting, to estimate the variation in landscape statistics. The resulting disturbance rates in each regime from one simulation (Run 2.2.1d) are shown in Figure 4.41.

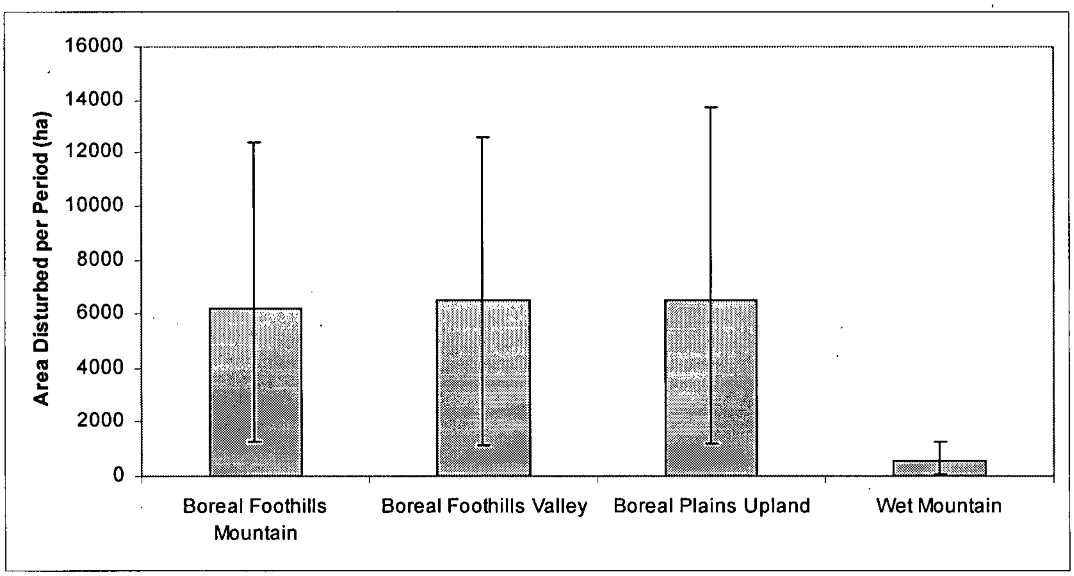


Figure 4.41. Average area disturbed in regimes per period –growth and historical disturbance scenario (Run 2.2.1d). Error bars indicate maximum and minimum observed values in area disturbed in each period.

Individual disturbance events were implemented with a range of event sizes using an exponential distribution based on the mean event size for each regime. The resulting pattern of disturbance event sizes from one simulation (Run 2.2.1d) is shown in Figure 4.42.

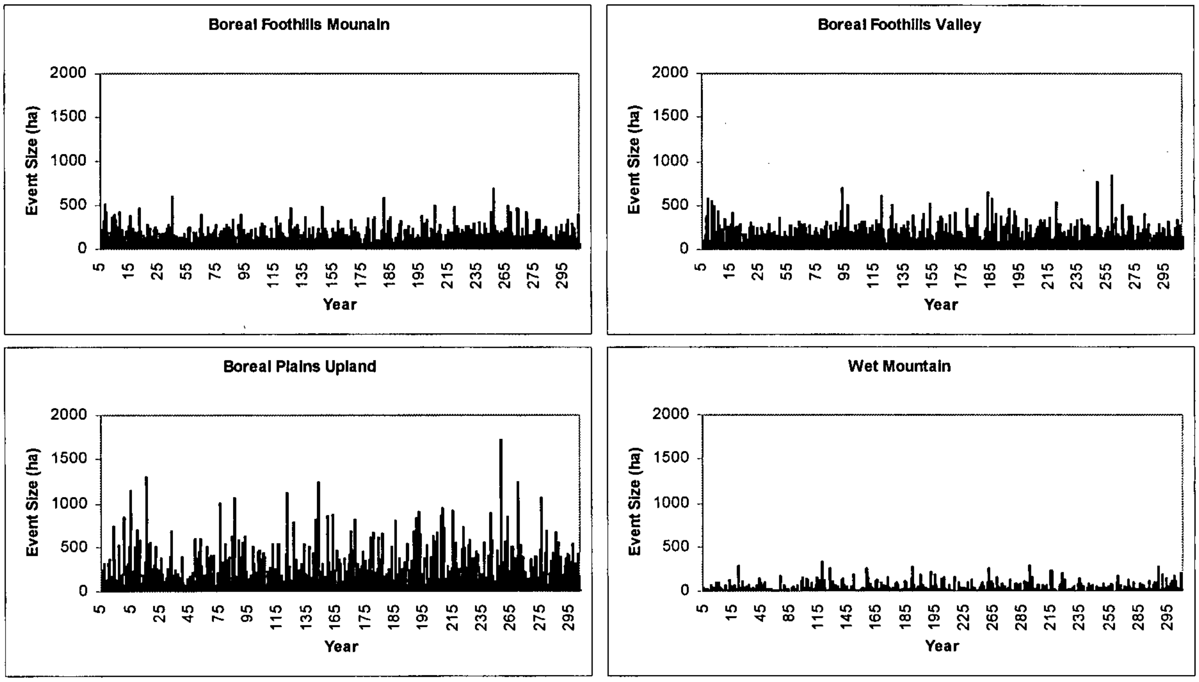


Figure 4.42. Disturbance event sizes in regimes –growth and historical disturbance scenario (Run 2.2.1d).

Figure 4.42 demonstrates that the Wet Mountain regime is characterized by small disturbance events that average 60 hectares and rarely exceed 200 hectares. The Boreal Plains Upland regime has frequent, large disturbances that average 200 hectares but are sometimes over 1000 hectares. The Boreal Foothills Mountain and Boreal Foothills Valley regimes have smaller disturbance sizes, averaging 80-90 hectares, though occasional events greater than 500 hectares occur.

Ten replications of this scenario were then analyzed (Runs 2.2.1d-2.2.10d). The dynamics of landscape statistics through the simulations are shown in Figures 4.43 to 4.46.

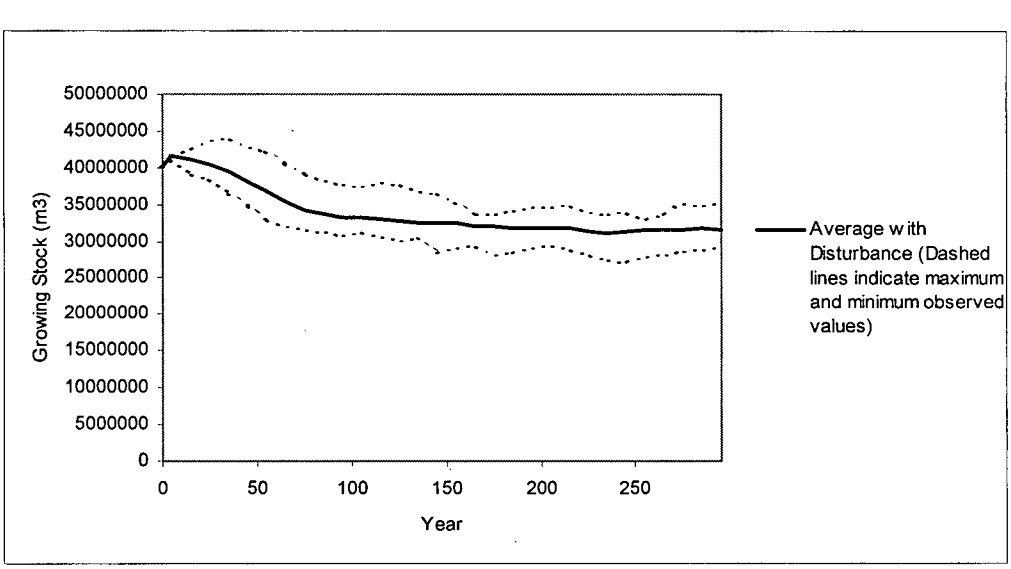


Figure 4.43. Total growing stock – growth and historical disturbance scenario (Runs 2.2.1d-2.2.10d).

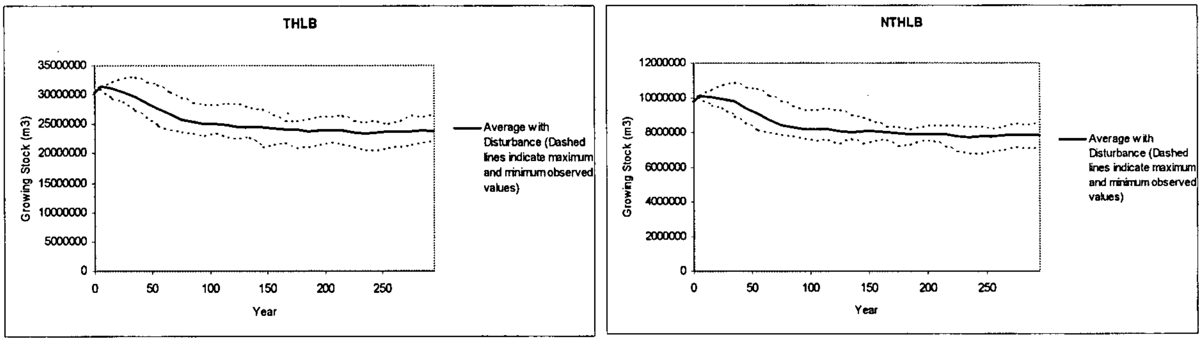


Figure 4.44. Growing stock in the THLB and NTHLB – growth and historical disturbance scenario (Runs 2.2.1d-2.2.10d).

Figures 4.43 and 4.44 demonstrate that the growing stock exhibits similar patterns on the THLB and NTHLB, as both are drawn down slightly from current levels, perhaps demonstrating the effectiveness of suppression efforts to date which may have increased growing stock to greater than historical levels. The total growing stock averages approximately 32 million m^3 after year 200, though the range of variation includes levels from 27 to 35 million m^3.

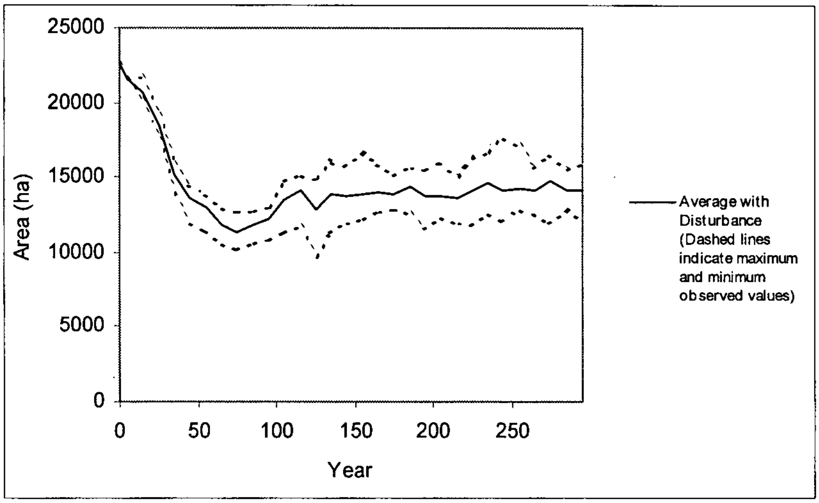


Figure 4.45. Area in small patches – growth and historical disturbance scenario (Runs 2.2.1d-2.2.10d).

Figure 4.45 shows that the area in small patches declines with the introduction of disturbance, as large events homogenize the landscape. The average area in small patches from years 200 to 300 is approximately 14,000 hectares, though it ranges from 12,000 to nearly 18,000 hectares.

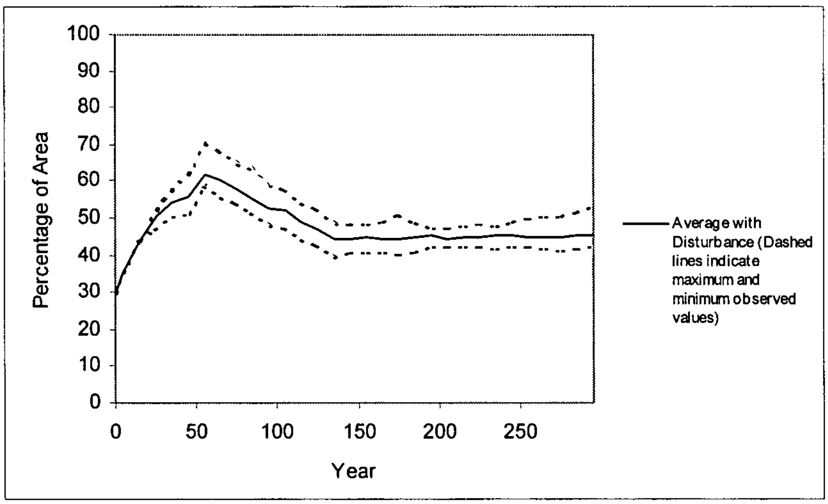


Figure 4.46. Late seral – growth and historical disturbance scenario (Runs 2.2.1d-2.2.10d).

Figure 4.46 shows that the amount of late seral stands rises initially through the simulations, but begins to decline again after year 60. This consistent pattern is an artifact of the starting conditions of the forest. The starting age-class distribution has many stands that soon move into the late seral class, though disturbance activity eventually draws down late seral stands. After year 200, the amount of late seral area has stabilized at approximately 45% of the landscape. The range of variation includes percentages of late seral area as low as 41% and as high as 53%. Late seral dynamics were virtually identical on the THLB and NTHLB.

4.2.2 Growth, Historical Disturbance and Harvest

When simulated alongside historical rates of natural disturbance, harvest targets dropped by approximately 51%, to an even-flow rate of 1,532,967 m^3 per period (Runs 2.3.1d-2.3.10d). Timber availability in relation to the harvest target is shown in Figure 4.47.

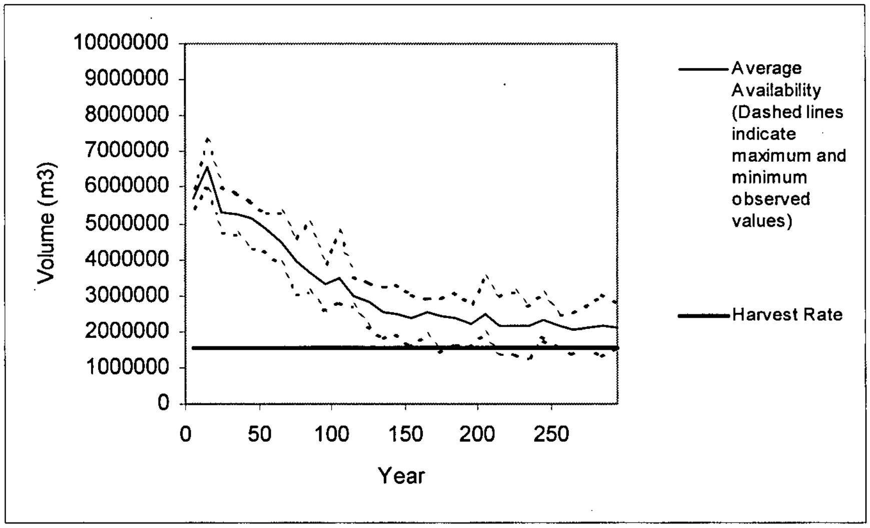


Figure 4.47. Harvest and availability – growth, historical disturbance and harvest scenario (Runs 2.3.1d-2.3.10d).

Figure 4.47 demonstrates that timber harvesting is again limited to a level that is approximately equal to the minimum amount of available timber. Availability is drawn down over the first 125 years of the simulation, and eventually reaches a fairly stable average of approximately 2.3 million m^3 per decade, which is approximately 1.45 times the harvest target. This excess of available timber provides one measure of a buffer that has been created against the variability in natural disturbance. The range of variation in availability is still wide, with peaks of over 3 million m^3 and minimums that are at or near the harvest target, resulting in constraining periods or even shortfalls. These shortfalls are infrequent enough to be within the risk tolerance or modest enough to be within the shortfall tolerance, and the restricted harvest rate allows available timber to subsequently recover and re-establish a buffer against future events.

The harvest and availability in individual regimes are shown in Figure 4.48.

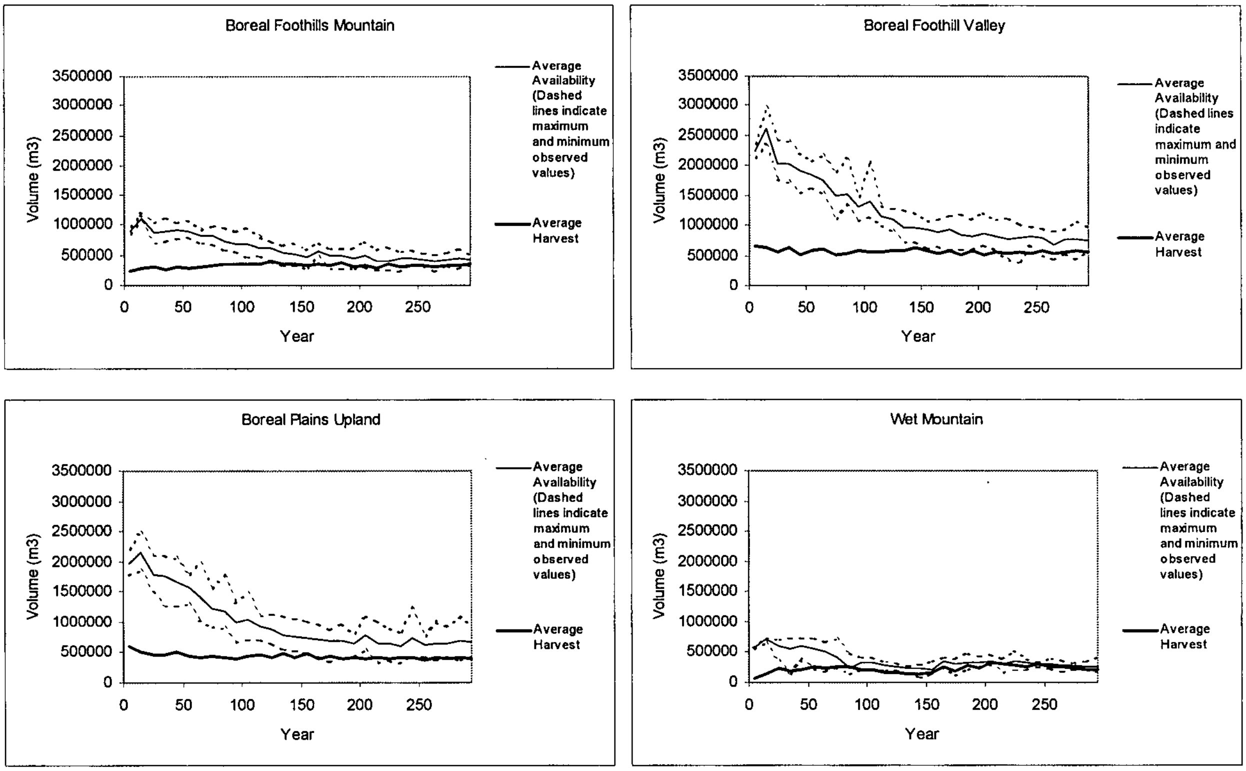


Figure 4.48. Harvest and availability in regimes - growth, historical disturbance and harvest scenario (Runs 2.3.1d-2.3.10d).

The Boreal Plains Upland regime (most variable disturbance rate) has the highest buffer of availability, averaging 1.65 times the harvest rate during the last 150 years of the simulations. The Wet Mountain regime, with the lowest disturbance rate and the least variability, has the least availability over the long term, averaging only 1.21 times the harvest rate. Another measure of the buffer can be estimated by calculating the difference between harvest rates in this scenario and the growth and harvest scenario, as shown in Figure 4.49.

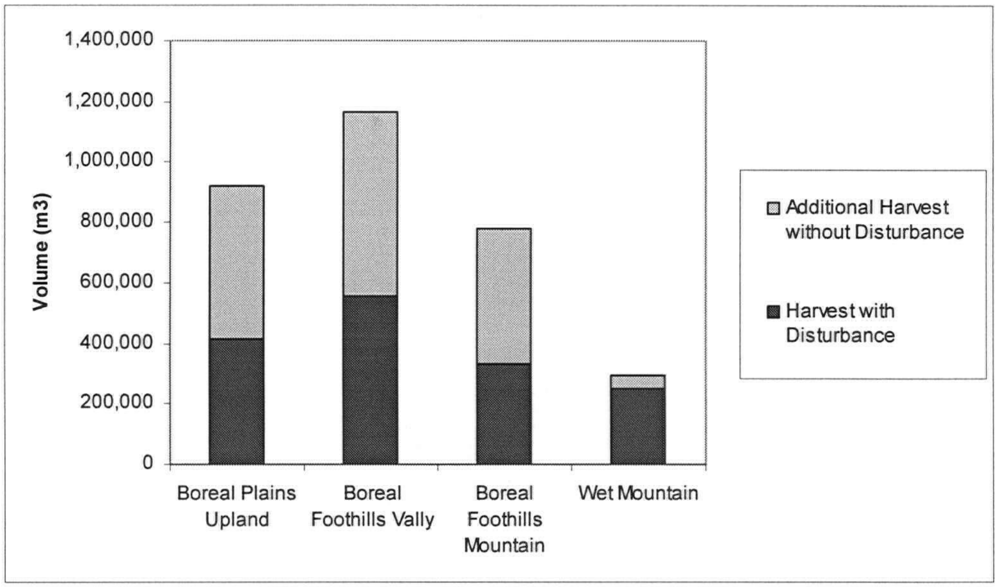


Figure 4.49. Average harvest flows in regimes – growth, historical disturbance and harvest scenario (Runs 2.3.1d-2.3.10d).

The buffer resulting from the reduced harvest flows is lowest in the Wet Mountain regime, where harvesting is only reduced by 11% with the introduction of disturbance. Harvesting in the Boreal Plains Upland, Boreal Foothills Valley, and Boreal Foothills Mountain is reduced by 56%, 53% and 58%, respectively. Although the harvest reductions for these three areas do not provide a perfect example of higher disturbance rates requiring larger harvest buffers (the Boreal Foothills Mountain has the lowest disturbance rate of the three but the highest harvest reduction), the disturbance rates for these three areas are in fact very similar, and this is reflected in the similar reductions in harvest. As the three areas do not share the same mosaic of stands and associated yields, this likely accounts for the slight differences between the specific responses to disturbance. Landscape statistics for these simulations are summarized in Table 4.4.

Table 4.4. Landscape statistics (years 200-300) – growth, historical disturbance and harvest scenario (Runs 2.3.1d-2.3.10d).

		Total	THLB	NTHLB
Late Seral %	Min	21.2	8.2	40.5
	Average	**27.4**	**13.3**	**48.4**
	Max	32.1	17.1	55.3
Growing Stock (m3)	Min	18,400,992	11,807,940	6,593,435
	Average	**22,646,652**	**14,799,897**	**7,849,737**
	Max	25,735,336	16,953,156	8,908,068
Area (ha) in Patches 0-50 ha	Min	36,239		
	Average	**40,288**		
	Max	43,201		

Table 4.4 shows that the introduction of harvesting has reduced growing stock and the percent area in late seral stands relative to the growth and historical disturbance scenario, however, these statistics remain largely unchanged on the NTHLB. The area in small patches has also increased dramatically as result of the dispersed harvesting pattern.

Profit per period, as compared with the no disturbance scenario, is illustrated in Figure 4.50.

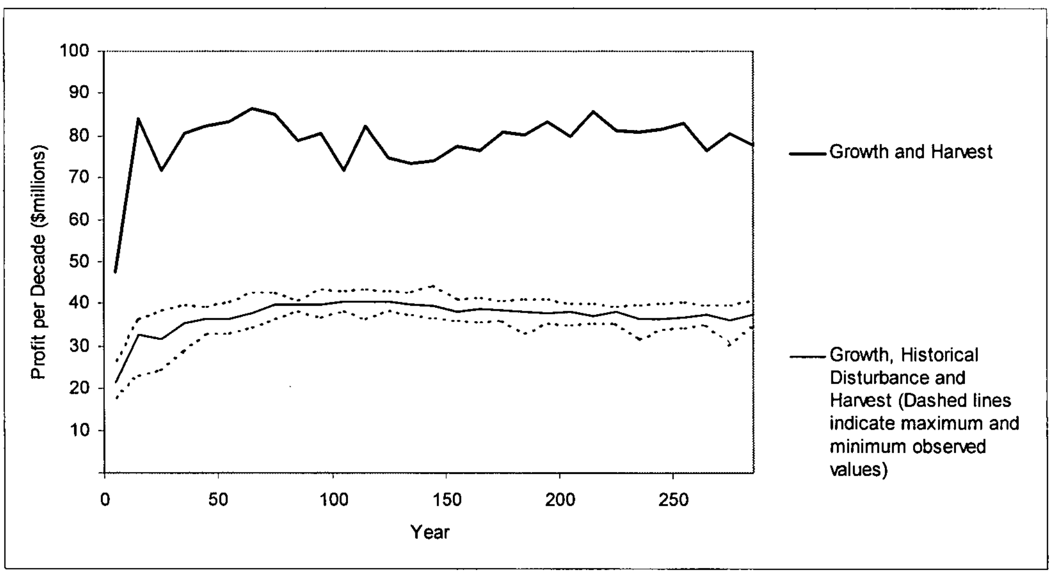
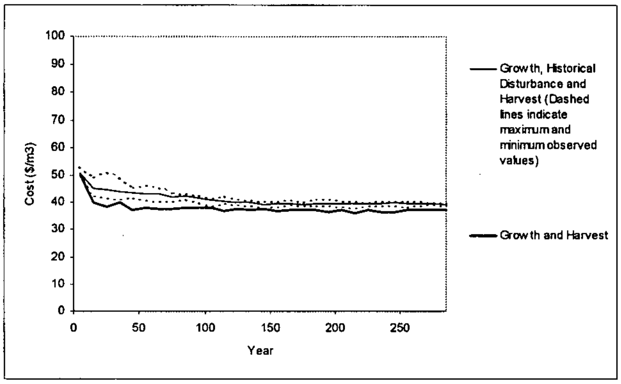


Figure 4.50. Comparison of profit per decade (Run 2.1.1d and Runs 2.3.1d-2.3.10d).

Figure 4.50 shows that the average profit rises initially, though more gradually than in the no disturbance scenario, because high costs associated with road network construction are spread across more periods. With an average profit of $37 million per decade, disturbance has produced a loss of approximately $40 million in profit per decade or $4 million per year. At a 4% discount rate, this translates into net present value of approximately $76 million, representing a reduction in the economic value of the land of approximately $100 million relative to the growth and harvesting scenario. The unit cost of extracting timber is higher under the historical disturbance scenario, as illustrated in Figure 4.51.



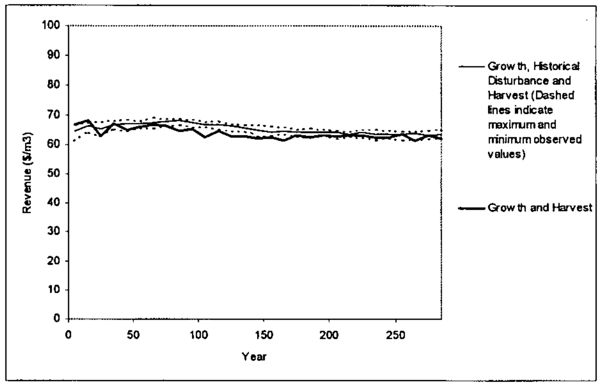


Figure 4.51. Comparison of unit costs and revenues (Run 2.1.1d and Runs 2.3.1d-2.3.10d).

The average unit cost is approximately $37.96/ m^3 without disturbance and approximately $41.15/ m^3 with disturbance. Unit costs increase because the lower rate of harvest still requires access over much of the landbase. However, Figure 4.51 also illustrates that unit revenue increases slightly. Unit revenue has risen from an average of $63.69/ m^3 without disturbance to $65.12/ m^3 with disturbance. This is because the less aggressive rate of harvest allows volumes to be made up from higher priority stands, which have a higher average value. Overall, unit profit decreases, from an average of $25.73/ m^3 under the no disturbance scenario to an average of $23.97/ m^3 with disturbance.

4.2.3 Growth, Suppressed Disturbance and Harvest

Disturbance suppression was simulated by reducing the size of disturbance events (Runs 2.4.1d-2.4.10d). Simulations were conducted with harvesting and disturbance, however, disturbance event sizes were limited to a fixed percentage of their targets (30%). The resulting disturbance rates in each regime from one run (2.4.1d) are shown in Figure 4.52.

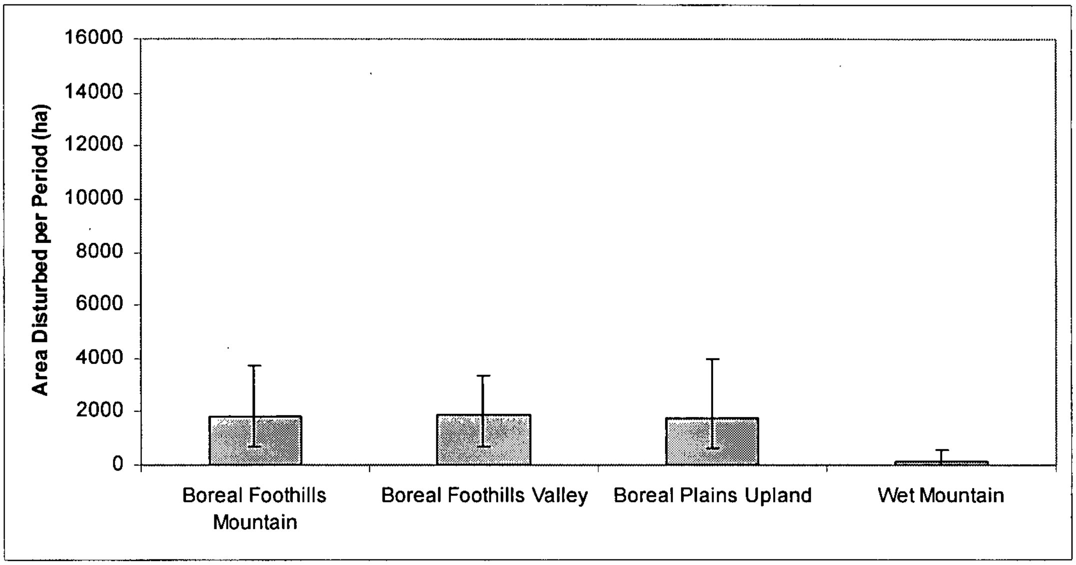


Figure 4.52. Average area disturbed in regimes per period – growth, suppressed disturbance and harvest scenario (Run 2.4.1d). Error bars indicate maximum and minimum observed values in area disturbed in each period.

Comparing Figure 4.52 with Figure 4.41 shows that suppression has reduced the average area disturbed in all regimes. The variation in disturbed area has also been reduced with the suppression of event sizes. The resulting pattern of disturbance event sizes from this simulation (Run 2.4.1d) is shown in Figure 4.53.

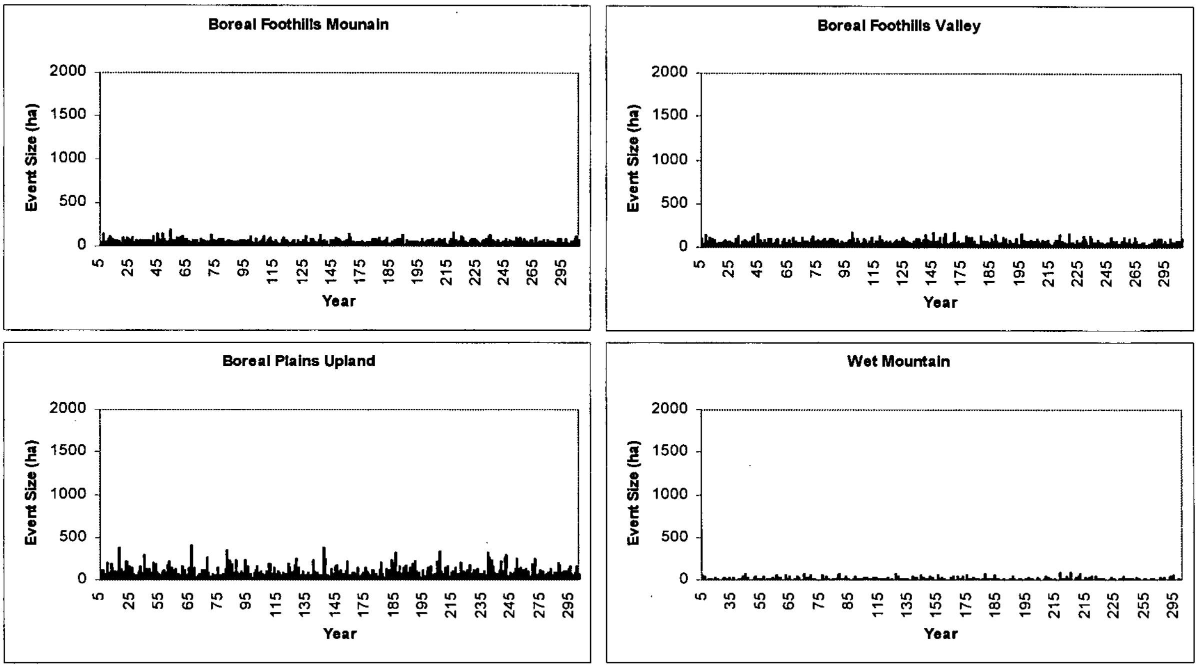


Figure 4.53. Disturbance event sizes in regimes – growth, suppressed disturbance and harvest scenario (Run 2.4.1d).

Comparing Figure 4.53 with Figure 4.42 confirms that the size of disturbance events has been reduced in all regimes. The Boreal Plains Upland regime still has the largest event sizes, though the largest events are now less than 500 hectares. Timber availability in relation to the harvest target is shown in Figure 4.54.

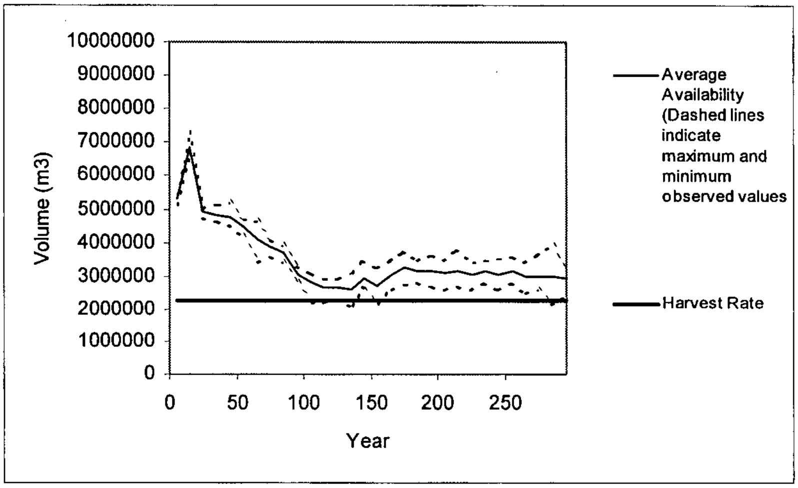


Figure 4.54. Harvest and availability – growth, suppressed disturbance and harvest scenario (Runs 2.4.1d-2.4.10d).

Figure 4.54 shows that by suppressing disturbance events, timber harvesting is still limited to a level that is approximately equal to the minimum amount of available timber, which now occurs in years 100 to 150, and again in the final two decades. Availability over the entire landscape increased relative to the historical disturbance scenario to a long-term average of approximately 3.0 million m^3 per decade. However, with the increased harvest, availability is now only 1.36 times the harvest rate, (a decrease relative to the historical disturbance scenario). The variability in available timber is also reduced with the introduction of suppression, with peaks of approximately 3.6 million m^3. The effect of this suppression on harvest flows within regimes is demonstrated in Figure 4.55.

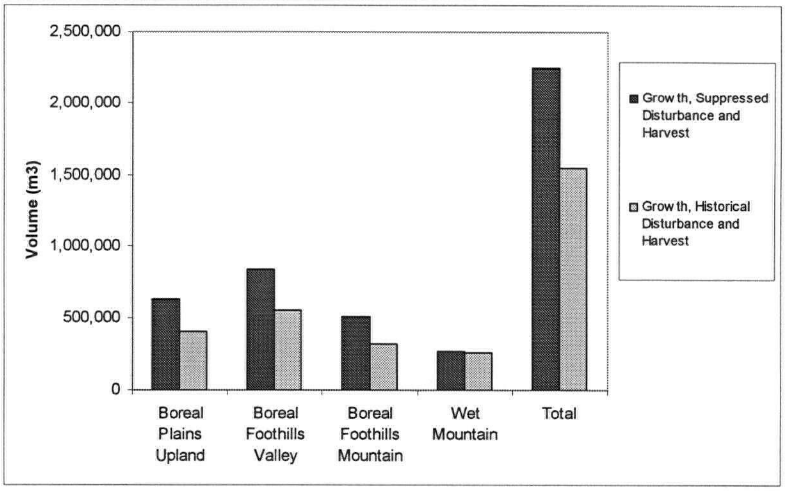


Figure 4.55. Average harvest flows with suppressed disturbance and historical disturbance (Runs 2.3.1d-2.3.10d and Runs 2.4.1d-2.4.10d).

Overall, harvest rates rose by approximately 46% with the suppression of all disturbance events to 30% of their target size. Only a modest 2% increase in harvest occurred in the Wet Mountain regime, though the other regimes had increased harvest flows of 53% to 57%. Landscape statistics at the end of these simulations are summarized in Table 4.5.

Table 4.5. Landscape statistics (years 200-300) – growth, suppressed disturbance and harvest scenario (Runs 2.4.1d-2.4.10d).

		Total	THLB	NTHLB
Late Seral %	Min	36.9	13.9	71.0
	Average	**40.5**	**16.7**	**75.8**
	Max	43.7	19.7	79.9
Growing Stock	Min	29,750,960	18,137,588	11,424,686
	Average	**31,761,642**	**19,608,365**	**12,157,294**
	Max	33,951,060	21,097,800	12,857,677
Area in Patches 0-50 ha	Min	58,710		
	Average	**62,153**		
	Max	66,578		

Comparing Table 4.5 with Table 4.4 shows that in addition to increasing the sustainable harvest rate, suppression has led to large increases in the average growing stock and the percent area in late seral stands. The area in small patches has also increased because of increased rates of dispersed harvesting, and a decrease in large disturbance events that otherwise homogenize the landscape.

4.2.4 Growth, Conditionally Suppressed Disturbance and Harvest

Disturbance suppression was then modeled 'conditionally' by assuming that most disturbance events could be reduced in size, but the largest disturbance events would be beyond human control (Runs 2.5.1d – 2.5.10d). Events beyond a given threshold were allowed to spread unconstrained to the size that would occur without suppression. For these simulations, 500 hectares was chosen to represent event sizes that are beyond human control. This affected a percentage of disturbance events in each regime, as outlined in Table 4.6.

Table 4.6. Percentage of disturbance events subject to conditional suppression in TFL 48 Block 4.

		Average Disturbance Size (ha)	Percentage of Events Suppressed
Boreal Plains (Upland)		200	91.79
Boreal Foothills	Valley	90	99.61
	Mountain	80	99.80
Wet Mountain		62	99.97

As Table 4.6 shows, conditional suppression assumes that only very rare events (0.03%) in the Wet Mountain regime are beyond control. The Boreal Foothills Valley and Boreal Foothills Mountain regimes have some rare events that are beyond control (0.4% and 0.2% respectively), and approximately 8% of events in the Boreal Plains are uncontrollable. The resulting disturbance rates in each regime from one simulation (Run 2.5.1d) are shown in Figure 4.56.

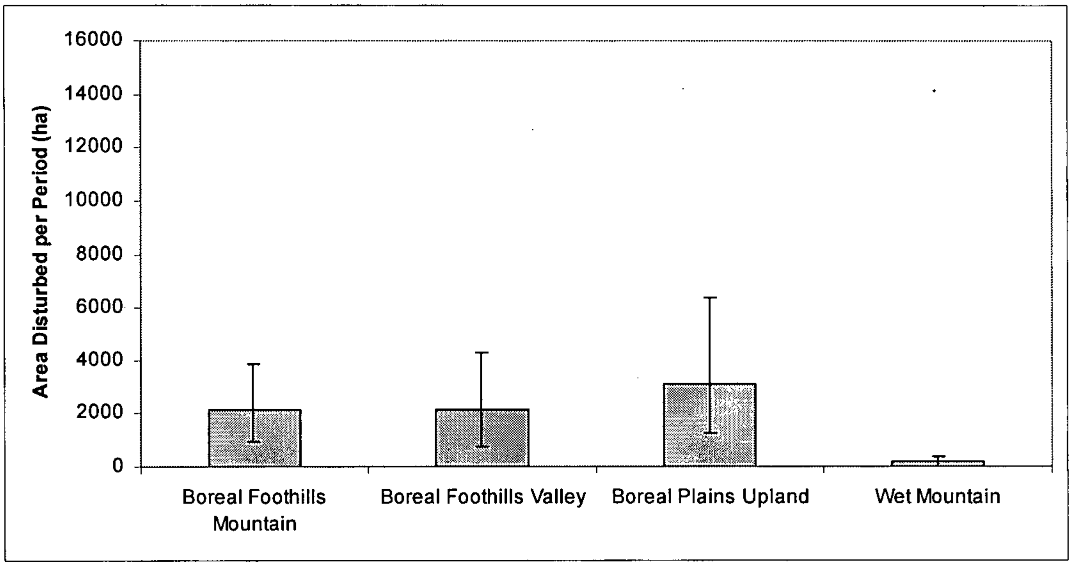


Figure 4.56. Average area disturbed in regimes per period (Run 2.5.1d) – growth, conditionally suppressed disturbance and harvest scenario. Error bars indicate maximum and minimum observed values in area disturbed in each period.

Comparing Figure 4.56 to Figure 4.52 shows that by allowing the largest events to spread unconstrained, disturbance area and the variability in disturbed area increase, mainly in the Boreal Plains Upland regime. The resulting pattern of disturbance event sizes from one simulation (Run 2.5.1d) is shown in Figure 4.57.

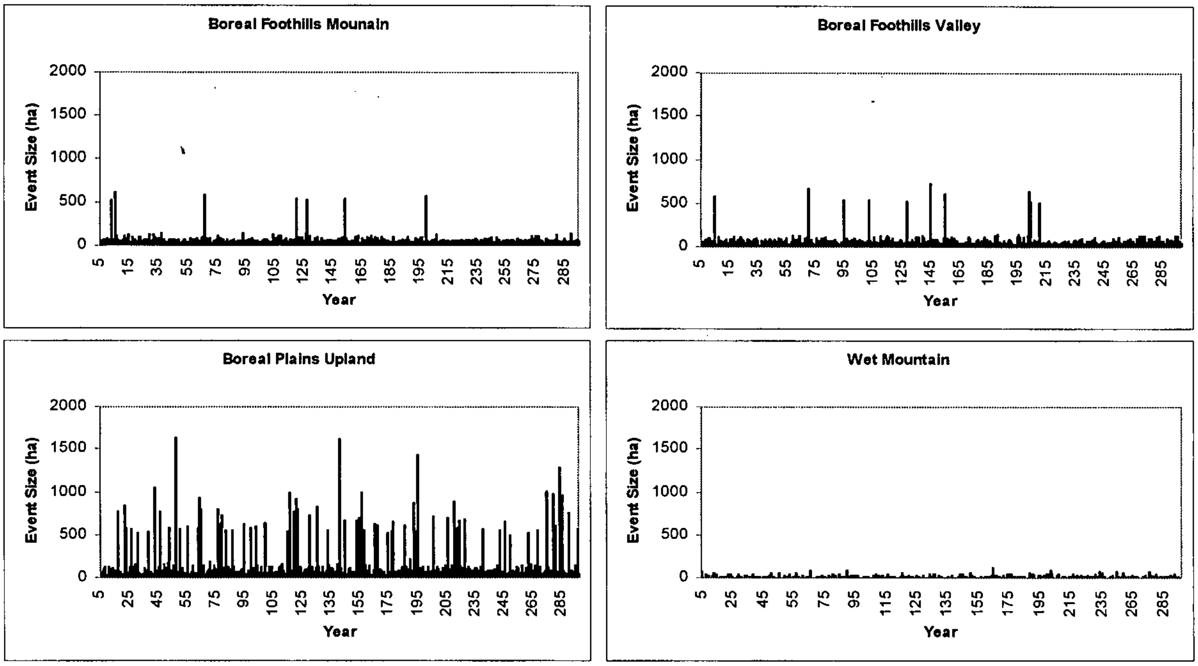


Figure 4.57. Disturbance event sizes in regimes (Run 2.5.1d) – growth, conditionally suppressed disturbance and harvest scenario.

Overall, when conditional suppression was used, 98.3% of disturbance events were suppressed. Unsuppressed events happened occasionally in the Boreal Foothills Mountain and Boreal Foothills Valley regimes, but were quite regular in the Boreal Plains Upland regime, sometimes exceeding 1000 hectares. The largest event observed across all ten simulations was 1743 hectares, in the Boreal Plains Upland regime.

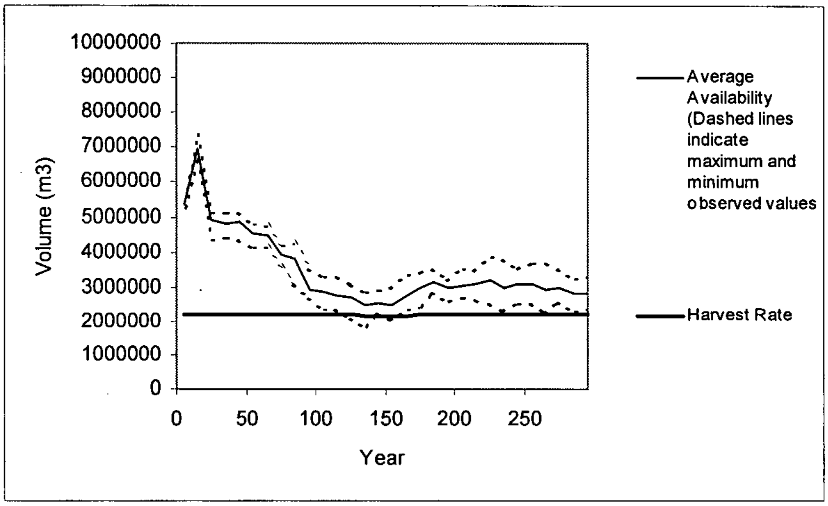


Figure 4.58. Harvest and availability – growth, conditionally suppressed disturbance and harvest scenario (Runs 2.5.1d-2.5.10d).

Available timber, as shown in Figure 4.58, averages just below 3.0 million m^3 per decade after year 150, though it remains at 1.36 times the harvest rate. However, the variability in available timber increased with the introduction of some large, unsuppressed disturbance events, and now shows peaks of nearly 4 million m^3 and more periods with minimums that are close to the harvest target. This is because occasional large disturbances create large amounts of available timber for salvaging in the short-term, but subsequently reduces availability to much lower levels. The effect of this scenario on harvest flows within regimes is demonstrated in Figure 4.59.

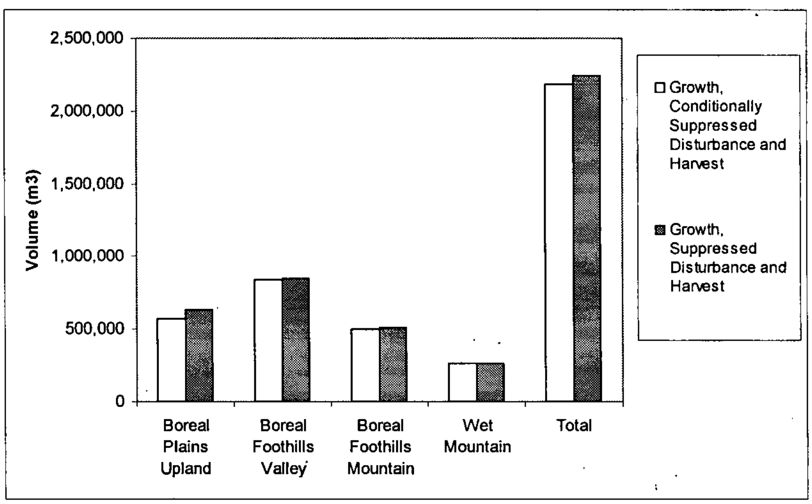


Figure 4.59. Average harvest flows with suppressed disturbance and conditionally suppressed disturbance (Runs 2.4.1d-2.4.10d and Runs 2.5.1d-2.5.10d).

Figure 4.59 shows that allowing larger disturbance events to spread unconstrained has reduced the overall harvest by approximately 3% relative to full suppression, though this reduction is almost entirely within the Boreal Plains Upland regime. The buffer in terms of harvest rates established under the assumption of full suppression remained largely unchanged in the Boreal Foothills Valley and Boreal Foothills Mountain regimes, but had to increase in the Boreal Plains Upland regime.

Landscape statistics at the end of these simulations are summarized in Table 4.7.

Table 4.7. Landscape statistics (years 200-300) – growth, conditionally suppressed disturbance and harvest scenario (Runs 2.5.1d-2.5.10d).

		Total	THLB	NTHLB
Late Seral %	Min	34.2	11.4	67.7
	Average	**38.4**	**15.2**	**72.9**
	Max	46.0	21.3	82.7
Growing Stock	Min	27,864,312	17,053,500	10,681,781
	Average	**30,188,458**	**18,603,392**	**11,588,506**
	Max	34,676,512	21,559,304	13,121,646
Area in Patches 0-50 ha	Min	55,974		
	Average	**59,833**		
	Max	63,243		

Comparing Table 4.7 with Table 4.4 and Table 4.3, shows the average growing stock and percent area in late seral stands remains higher than with no suppression, though not as high as the full suppression scenario. The range of variation in these indicators is also wider. This is because suppression allows growing stock and late seral stands to accumulate to high levels, though the continued presence of occasional catastrophic disturbance events can drastically reduce them. The area in small patches has also decreased with the inclusion of occasional large disturbances, which have a homogenizing effect on the landscape.

4.2.5 Scenario Summary

To provide an overall comparison of the scenarios, the average values and the range of variation of landscape statistics (late seral percent area, growing stock, and the area in small patches) resulting from each scenario are summarized in Figures 4.60 through 4.62.

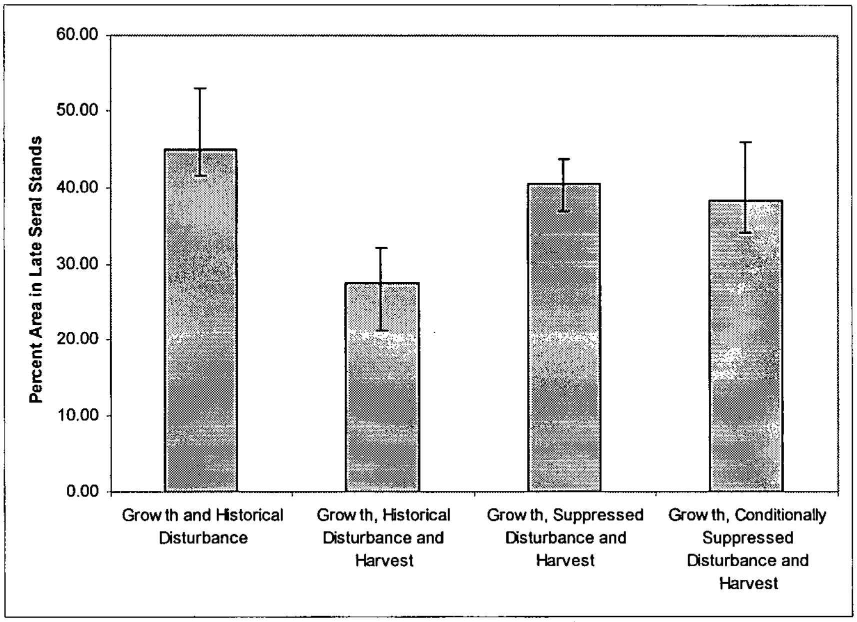


Figure 4.60. Late seral – scenario summary. Error bars indicate the maximum and minimum observed values from ten runs.

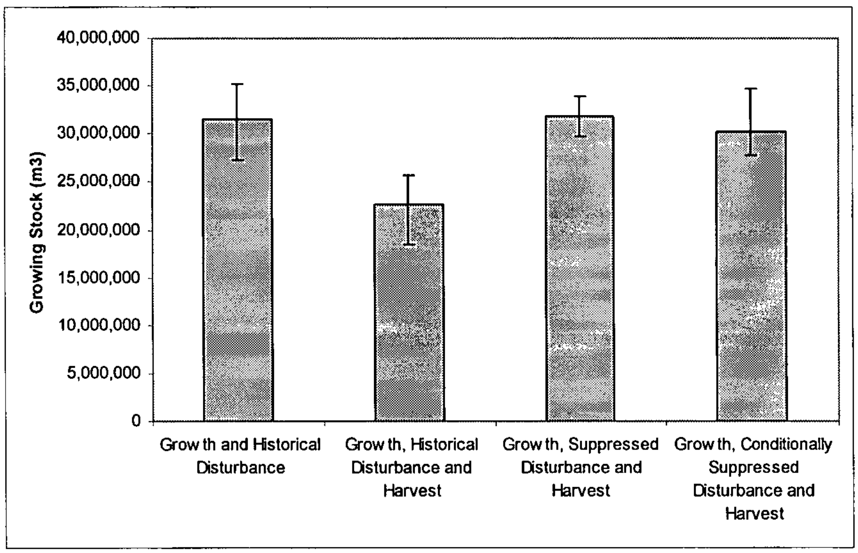


Figure 4.61. Growing stock – scenario summary. Error bars indicate the maximum and minimum observed values from ten runs.

Figures 4.60 and 4.61 show that without suppression, harvesting reduces late seral percents and growing stock. When suppression is included, the average values for total growing stock and percent area in late seral stands increase, and often remain within or close to the natural range of variation (NRV) estimated from the growth and disturbance scenario. Referring back to Tables 4.5 and 4.7 confirms that this is mainly attributable to increases in the NTHLB, where suppressed disturbance and the absence of harvesting allow large accumulations of growing stock and late seral stands. The range of variation decreases with the introduction of suppression, but increases with conditional suppression. This happens because suppressed disturbance in combination with a constrained rate of harvest allows growing stock and late seral stands to accumulate, but occasional catastrophic events can still drastically reduce them.

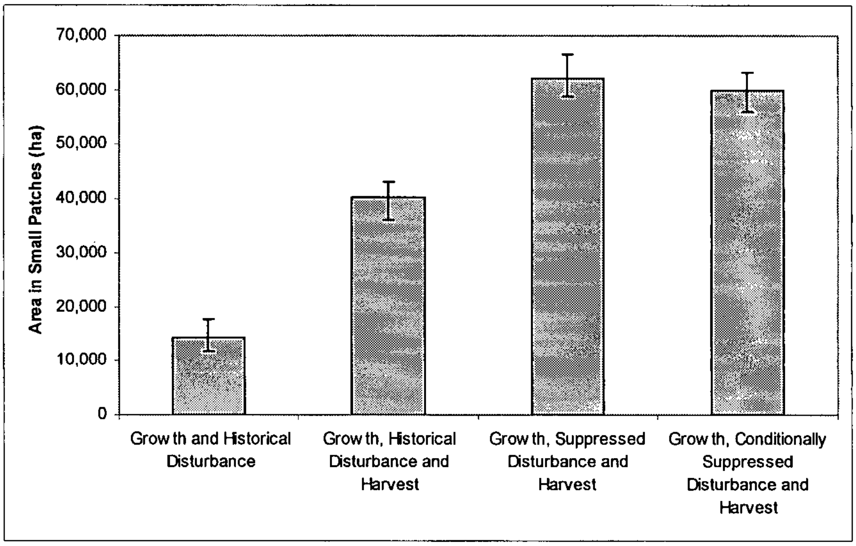


Figure 4.62. Area in small patches – scenario summary. Error bars indicate the maximum and minimum observed values from ten runs.

In Figure 4.62 the area in small patches is higher than the NRV for all of the harvesting scenarios. This demonstrates the dramatic impact that a dispersed pattern of harvesting can have on landscape condition, even with the continued presence of random disturbance activity that homogenizes areas of fragmented forest.

4.2.6 Economic Analysis of Suppression and Risk

When suppression was turned on in the model, harvest rates, profits and net present value all increased. Costs associated with the suppression activities themselves (i.e. prevention, patrols, initial attack and mop-up) have been excluded, but the differences in cash-flow provide an estimate of the value that these activities would have in terms of increased harvesting. Profits from the suppression scenario and the full historical disturbance scenario are illustrated in Figure 4.63.

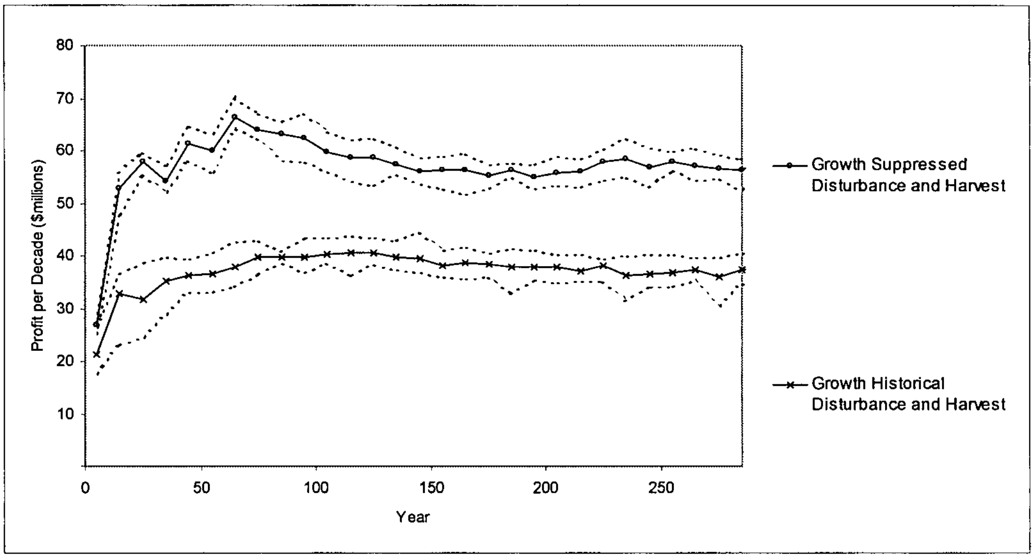


Figure 4.63. Average profit per period - suppressed disturbance and historical disturbance (Runs 2.3.1d-2.3.10d and Runs 2.4.1d-2.4.10d). Dashed lines indicate maximum and minimum observed values.

With suppression, an average profit of $57 million per decade was observed, which is an increase of approximately $20 million relative to the full disturbance scenario. Unit profit increased to $25.39 per cubic meter and the net present value of the land increased to $120 million. When conditional suppression was used, average profit was reduced to an average of $55 million per decade, as shown in Figure 4.64.

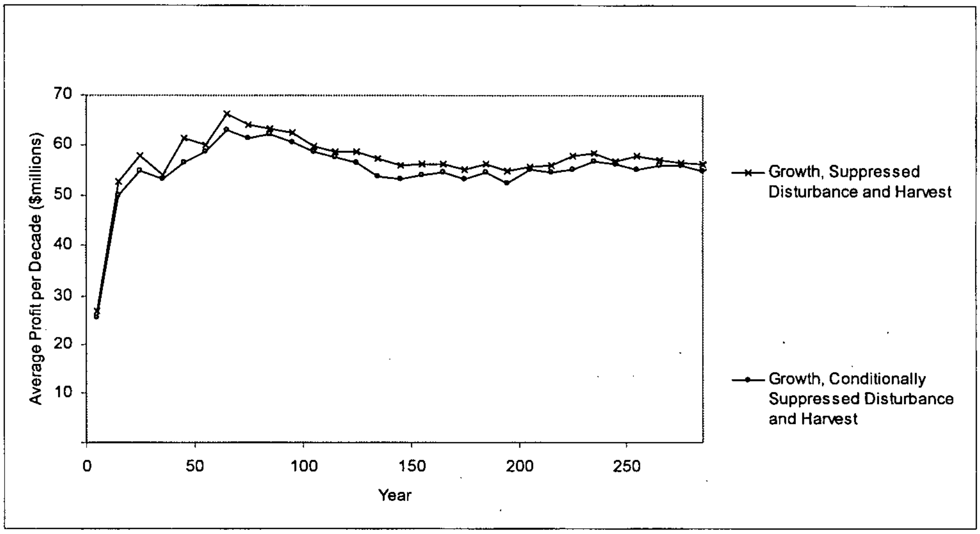


Figure 4.64. Average profit per period - suppressed disturbance and conditionally suppressed disturbance (Runs 2.3.1d-2.3.10d and Runs 2.4.1d-2.4.10d).

Compared to historical rates of disturbance, suppressing all disturbance events under 500 hectares results in an increased profit of only $18 million per decade. This means that the cost of the 1.7% of events that create the largest disturbances can be estimated at approximately $2 million per decade or $200,000 per year. Net present value under the three disturbance and harvesting scenarios are summarized in Figure 4.65.

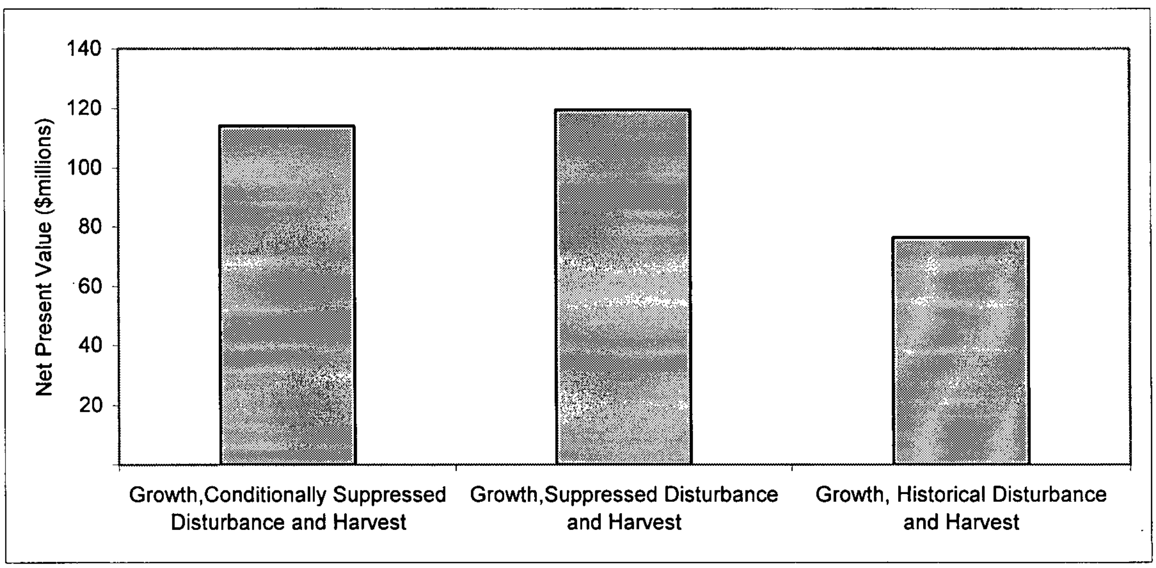


Figure 4.65. Net present value – scenario summary.

Figure 4.65 shows that suppressing all disturbance events to 30% of their natural size increases the NPV of this forest from approximately $76 million to $120 million. This drops to $114 million with conditional suppression, indicating that allowing the 1.7% of events that create the largest disturbances to remain unsuppressed reduces the net present value of this forest by approximately $6 million.

A final exercise was conducted to explore the cost of maintaining the level of risk tolerance (0.1 probability of failure). Using the conditional suppression scenario, harvest targets were set to fixed levels of risk, and the pattern of cash-flow was tracked from ten replications at each risk level (Runs 2.51d to 2.8.10d, see Appendix 1 for run numbers that correspond to each risk level). Figure 4.66 shows the changes in net present value at four levels of risk. Note that where a risk value of 1.0 was tested, the lowest harvest target that contained that level of risk was used (since all harvest targets above that level would have a risk of 1.0).

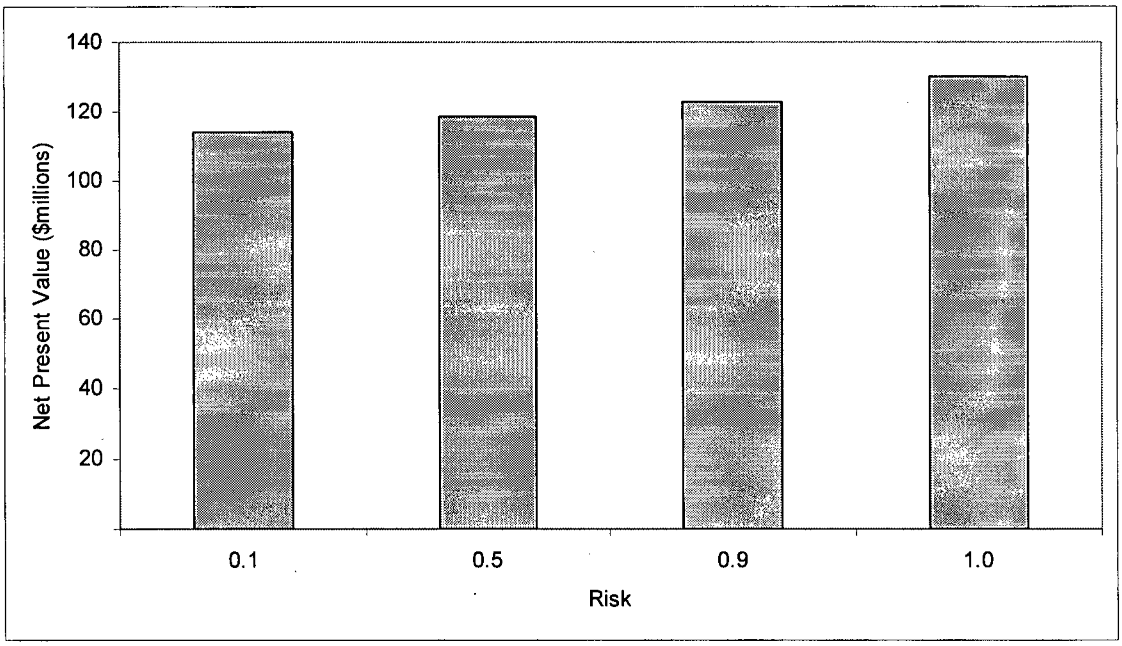


Figure 4.66. Average net present value from harvesting at four levels of risk (Runs 2.5.1d-2.8.10d).

Figure 4.66 shows that increasing risk tolerance increases net present value. Increasing the risk tolerance to 0.5 results in a net present value of $118 million, and increasing it to 1.0 results in a net present value of $130 million. Figure 4.67 illustrates the changing pattern of profit from ten simulations at each level of risk.

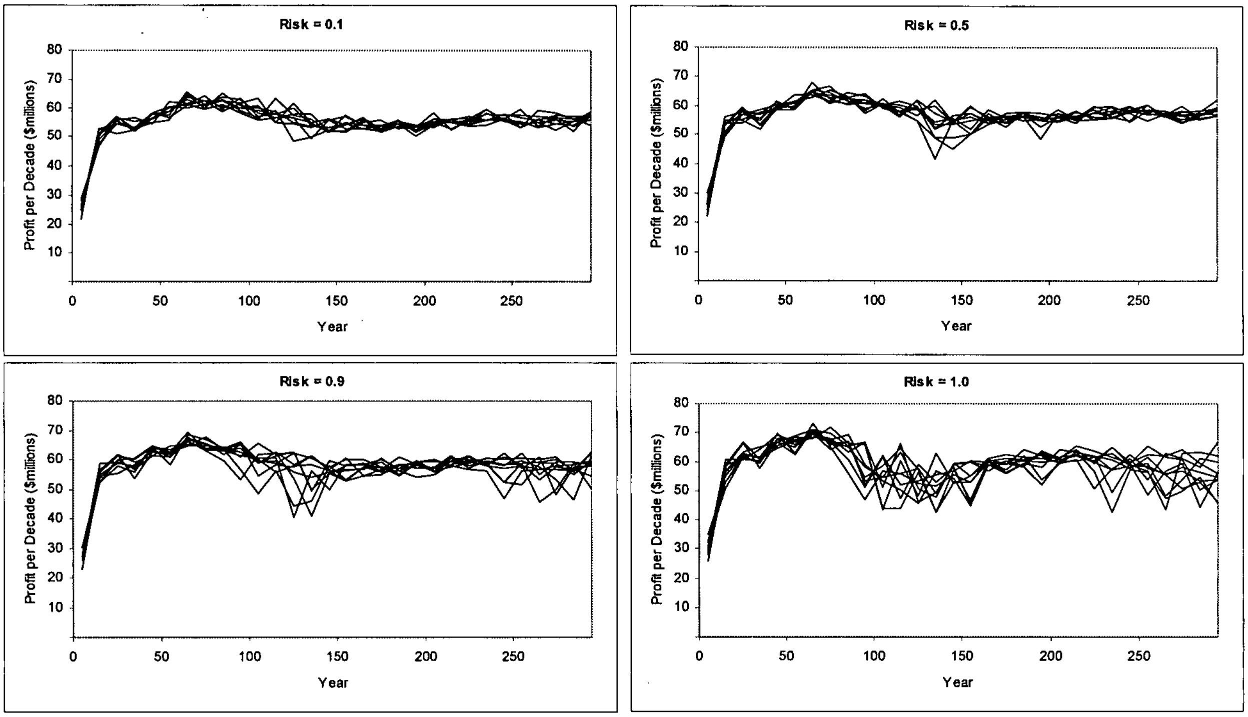


Figure 4.67. Profit per period from ten simulations of harvesting at four levels of risk (Runs 2.5.1d-2.8.10d).

Figure 4.67 shows that as harvest targets are increased, and a higher risk approach is taken, profits can rise to higher levels over the first 75 years. Beyond this time, profit becomes volatile and begins to decline, as buffer stocks are drawn down to levels that cannot absorb disturbance activity.

Figure 4.68 summarizes the long-term profitability by showing the average profit per decade after year 150, along with the range of values observed per period.

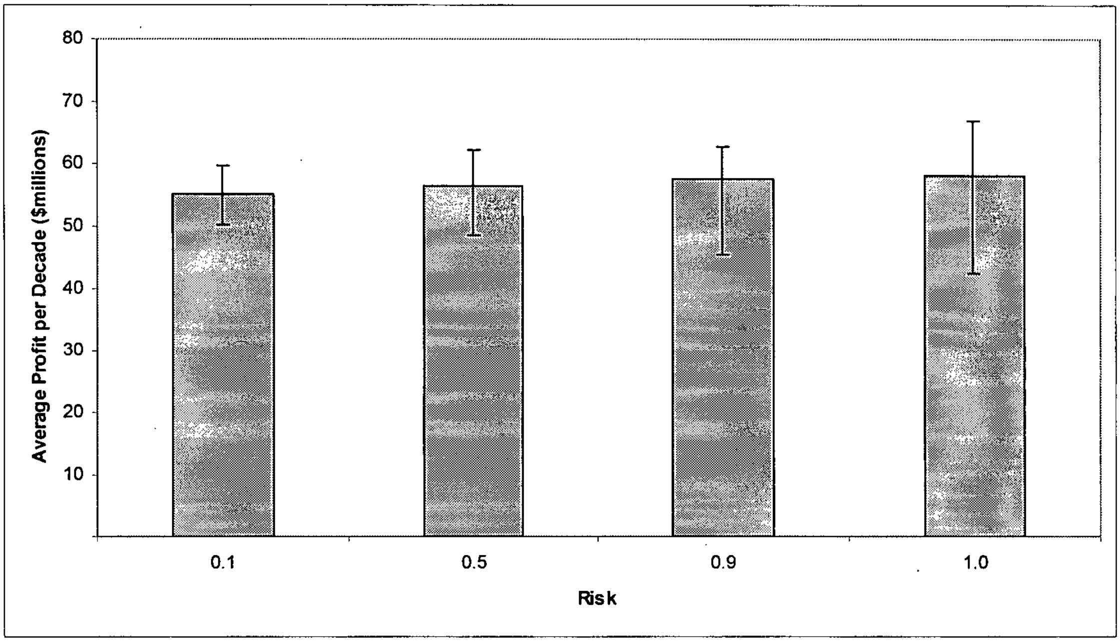


Figure 4.68. Average long-term profit per period (years 150-300) from harvesting at four levels of risk (Runs 2.5.1d-2.8.10d). Error bars indicate the maximum and minimum observed values from ten runs.

Harvesting at a 0.1 risk level delivers the most stable long-term profitability at $55 million per decade, along with minimums of $50 million and peaks of just under $60 million. Increasing risk to 0.5 increases long-term profitability to approximately 56.5 million, though drops to $48 million begin to occur. Increasing risk to 0.9 and 1.0 results in only modest gains to long-term profitability, with increasing drops in profit observed. Using a risk level of 1.0 results in average long-term profits of $58 million, though this drops to levels as low as $42 million in some periods. This demonstrates that although discounting may favour a riskier approach to harvesting because of higher profits in the short term, long term profits may increase very little, and be accompanied by periods with much lower profits.

5.0 Discussion

The range of variation for many indicators of landscape condition depends on both the disturbance characteristics for the area and the scale of the area. Depending on the relationship between disturbance rates, disturbance event sizes, and landscape size, measures of landscape condition such as growing stock or seral stage amounts can be somewhat stable or highly unstable. The more volatile the disturbance rate, the wider the range of variation. Small landscapes that are subject to relatively small scale, predictable rates of disturbance can still have wide ranging landscape conditions, as was demonstrated on the Grid landscape.

Estimates of sustainable harvest targets developed for the Grid landscape show that harvesting is constrained by both the amount and volatility of disturbance. When disturbance is not included, the model predicts equal harvest flows (on average) from each of the two disturbance regimes. Because the two regimes have very different disturbance characteristics, including disturbance results in different harvest levels from each regime. In Block 4, harvest flows from each regime also reflect different disturbance rates. By explicitly modelling disturbance in this way, a better understanding of the long-term supply profile of the forest can be gained.

Quantifying risk using a logistic model was shown to be an effective way of estimating a sustainable harvest targets for a given risk tolerance. Higher levels of risk tolerance allow higher rates of harvesting, although the harvest becomes more variable. Although the maintenance of harvest volume was the basis for quantifying risk in this thesis, the same methods could also be applied to other indicators of sustainability such as cash-flow, or even the maintenance of various non-timber values.

Scale is a crucial consideration when the sustainability of harvesting is evaluated. Smaller landscapes can be much more vulnerable to catastrophic losses, which can lead to highly constrained harvest targets. Time is the other important scale to consider, and even large landscapes are subject to catastrophic losses that render any harvest target unsustainable, provided a sufficiently long timescale is considered. Very different estimates of sustainability are obtained, depending on the temporal scale. Short temporal scales produce higher 'sustainable' harvest levels than long temporal scales.

Similarly, an evaluation of sustainability on portions of a landscape in isolation can underestimate the potential of these areas to make large contributions to an overall timber supply. This was demonstrated on the Grid database by coupling an area that is highly constrained by volatile disturbance rates with a more stable area, and showing that the constrained area can still make large contributions to an overall stable harvest. This has implications for timber supply area and tenure design. When small areas that may seem highly constrained by periodic large disturbance events are considered, allowing flexibility in supply from a wider area (particularly areas that may be less prone to such disturbances) can create an entirely new picture of what is sustainable.

Salvage harvesting also has a dramatic impact on timber supply, allowing shortfalls in volume that result from peak disturbance periods to be made up by the removal of damaged timber. In the current model, disturbed stands are only salvaged until the harvest target for the period is met, potentially leaving large areas of disturbed and merchantable timber under-utilized. With a more flexible approach, peaks in availability resulting from disturbance could be utilized more efficiently, and provide more managed stand areas with higher growth rates. This could allow growing stock to recover more quickly, and produce higher estimates of sustainable harvest rates.

A reduced harvest target that accounts for disturbance can be thought of as a buffer, and increasing amounts of disturbance as well as increasing volatility in disturbance requires larger buffers. Harvest targets are constrained to approximately the minimum availability levels encountered throughout the simulations, but the landscape typically exists with a quantity of timber availability that is greater than the harvest target. This available timber provides another measure of a buffer, creating a landscape that is capable of withstanding variation in disturbance rates without impacting the timber harvest. These buffers have the ability to absorb catastrophic disturbance events that reduce available timber to levels at or near the harvest level. However, these events must be infrequent enough to allow the buffer to recover in time for the next event. Buffering against natural disturbance in terms of excess available timber can provide other benefits, such as increased amounts of old forest on the landscape. However, we should also remain aware that the buffer is there to provide an alternative when disturbance limits harvesting opportunities elsewhere, and these extra amounts of old forest may be drawn down along with the buffer when needed.

Suppressing disturbance can have a drastic effect on both harvest targets and landscape statistics. If we assume our suppression activities are highly successful, harvest targets can rise, and we can experience both the economic benefits flowing from the commercial landbase, as well the as non-timber benefits attributable to increasing amounts of contiguous old forest that accumulate in non-commercial areas. Whether this is a realistic assumption is questionable. One only has to look to recent examples in North America of extreme conditions that have led to fires that remained largely beyond human control. When suppression is modelled to control only small and medium sized events, landscape statistics such as late seral area and growing stock remain higher on average, although the range of variation increases. This is because suppressed disturbance in combination with a constrained rate of harvest allows growing stock and late seral stands to accumulate, but occasional catastrophic events can still drastically reduce them.

A dispersed pattern of harvesting creates large increases in the area in small patches, even with the continued presence of disturbance that homogenizes areas of fragmented forest. Recent trends away from the practice of small-scale, dispersed harvest openings could offset these effects.

Natural disturbance has a quantifiable cost, and when the model was applied to the large TFL 48 Block 4 landscape, the cost of historical rates of natural disturbance were estimated at $4 million per year, harvests were reduced by 51%, and the net present value of the forest was reduced by 57%. Suppressing disturbance to 30% of historical rates increased profit by $2 million per year, increased harvesting by 46%, and increased net present value by 58%. If the largest 1.7% of events cannot be suppressed, profit is reduced by $200,000 per year, harvesting is reduced by 3%, and net present value is decreased by 3.5%. To put this in perspective, direct suppression costs for the 2.9 million hectare Dawson Creek Forest District (which TFL 48 Block 4 is a part) during an 11-year period from 1992 to 2002 totaled $3.7 million (Grayston 2003). This translates into an annual cost of approximately $336,000, for an area roughly ten times the size of Block 4. Furthermore, suppression may have reduced disturbance rates to levels even lower than the 30% reduction assumed in this thesis (DeLong 2003). Increasing risk tolerance produced higher short-term profits and net present value on Block 4, though as buffers are drawn down over the long-term, profits increased very little, and were accompanied by periods with much lower profits. When future profits are subject to higher risk, they may also be valued less by an investor, and consequently discounted at a higher rate. This could reduce net present value, and further offset the gains of a higher risk approach. Although the cash-flow estimates provided a useful way to quantify the relative economic benefits from scenarios, the model does not include the actual costs associated with different levels of suppression. If taxes and a profit margin for the firm were included along with suppression costs, estimates of the economic land rent could also be included.

The overall method of simulating disturbance that I have used, where event occurrence and event sizes are generated from empirical distributions, works well for landscapes where disturbance regimes can be described as occurring in large contiguous areas, such as whole watersheds or on south/north aspects. Where regimes are dispersed, a more complex approach may be needed. Taking an approach that more explicitly simulates the processes of disturbance might be necessary, and would also allow disturbance patterns to respond to shifts in species composition or other landscape conditions. Designing and implementing such a model would be a significant and expensive undertaking. The more simple approach that I have taken has the advantage of being easier in terms of both set-up and interpretation. In the end, the approach depends on the questions being asked of the model, and a simpler approach that adequately addresses the questions is often better than a complex one.

Similarly, timber supply analysis methods for public lands in British Columbia should use methods that are appropriate to the questions being asked by forest managers and stakeholders. Where a forecast of total harvest volume is the primary objective, deducting a quantity of non-recoverable losses, as is currently done, would seem to be an acceptable approach. However, when more detailed information on spatial statistics or supply profiles are desired, taking a more explicit approach is necessary. As this thesis demonstrated, deciding on how much of a reduction in timber supply to make in response to disturbance depends on our assumptions around suppression effectiveness and our ability to salvage disturbances. It also depends on the variability of disturbance, and whether we want to sustain harvesting through the most catastrophic years. By analyzing risk, we can choose whether we want to be conservative and ensure that commercial activity can be sustained through catastrophic years, or whether we are willing to accept periodic downturns.

6.0 Conclusion

This thesis explored the interaction between harvesting and disturbance in a spatially explicit forest model. The objectives of the thesis were to quantify risk based on the uncertainty of fire disturbance, to quantify timber supply buffers, to examine the effects of suppressing natural disturbance, to examine landscape attributes, and to examine economic aspects of disturbance. These objectives were achieved by first developing a model that simulates disturbance events within a spatially explicit harvest-scheduling simulator, and second, applying the model to a large landscape in northeastern BC. Although timing, location and extent of forest fires and other disturbances will always be uncertain, modelling exercises such as this can provide insight into how these events might impact landscape conditions and harvest targets, thereby guiding forest management. The inclusion of cash-flow in the model makes it a useful tool that could potentially guide investment decisions, and expenditures on suppression.

Opportunities for further research in this modelling environment remain. These include incorporating relationships between forest succession and disturbance patterns. Modelling succession in this way could demonstrate changes in stand composition with increasing rates of disturbance, rather than just shifts in the age-class structure and growing stock. Improvements in the representation of suppression could also be made to relate such things as stand attributes to suppression effectiveness. For example, fires that occur in younger stands or those with different fuel characteristics may have shorter flame lengths, making them easier to suppress. Management activities that manipulate the spatial arrangement of such stands to create 'fire-breaks' in the forest could then be examined, and the response of disturbance rates to these changes could be explored. A range of suppression scenarios that include varying amounts of expenditure could also provide the basis for a benefit/cost analysis. Finally, models of wildfire occurrence could be examined that incorporate more rare, but highly catastrophic events. However, we should not constrain forest management unduly, based on events that may be no more likely than wars, epidemics, or other rare catastrophes. It is always prudent to have a buffer against the unexpected, but we should not solely plan for the worst-case scenarios. Quantifying risk, as was done in this thesis, provides a better framework for decision-making where natural disturbance is a significant driver of forest ecosystems.

7.0 References

Anderson, A. 2003. Road projections for TFL 48 Block 4. Unpublished dataset. University of British Columbia, Vancouver, Canada.

Andison, D. 1996. Managing for Landscape Patterns in the Sub-Boreal Forests of British Columbia. PhD. Thesis, University of British Columbia, Vancouver, Canada. 197p.

Armstrong, G. 1999. A Stochastic Characterisation of the Natural Distrubance Regime of the Boreal Mixedwood Forest with Implications for Sustainable Forest Management. Canadian Journal of Forest Research. 29: 424-433.

Armstrong, G. 2000. Probabilistic Sustainability of Timber Supply Considering the Risk of Wildfire. SFMN Working Paper, University of Alberta Edmonton, Alta. 15p.

BCMOF. 2004. Log Market Reports. Revenue Branch, BC Ministry of Forests. http://www.for.gov.bc.ca/hva/timberp/amv.htm (visited 23/02/2004).

BCMOF. 2003. Average Hectares, Fires, and Dollars - Review of 2002 Fire Season. Protection Branch, BC Ministry of Forests. http://www.for.gov.bc.ca/protect/reports/HistoricalAverages.htm (visited 23/02/2004).

BCMOF. 1999. Developing Stand Density Management Regimes. Forest Practices Branch, BC Ministry of Forests. http://www.for.gov.bc.ca/hfp/pubs/stand_density_mgt/ (visited 23/02/2004).

BCMOF. 1998. Operational and Site Planning Regulation. Forest Practices Code. BC Ministry of Forests, Victoria, BC. http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcaregs/oplanreg/opr.htm (visited 23/02/2004).

BCMOF. 1995. Biodiversity Guidebook. Forest Practices Code. BC Ministry of Forests, Victoria, BC. 99p.

Bettinger and Sessions. 2003. Spatial Forest Planning – To Adopt, or Not to Adopt. Journal of Forestry. 101(2): 24-29.

Boychuck, D., and Martell, D. 1996. A Multistage Stochastic Programming Model for Sustainable Forest-Level Timber Supply Under Risk of Fire. Forest Science 42: 10-26.

Boychuck, D. and Perera, A. 1997. Modeling Temporal Variability of Boreal Landscape Age-Classes Under Different Fire Disturbance Regimes and Spatial Scales. Canadian Journal of Forest Research. 27: 1083-1094.

Boyland, M. 2002. Simulation and Optimization in Harvest Scheduling Models. ATLAS/SIMFOR Project Extension Report. University of British Columbia, Vancouver BC. 10p. http://www.forestry.ubc.ca/atlas-simfor/extension/reports.html (visited 01/04/2004).

Cameron, A. and Trivedi, P. 1998. Regression Analysis of Count Data. Cambridge University Press. Cambridge, UK. 411p.

Canfor. 2001. Tree Farm Licence 48 Timber Supply Analysis Information Package in Support of Management Plan 3. Canadian Forest Products Ltd., Chetwynd, BC. 108p.

Conrad, J., and Clark, C. 1987. Natural Resource Economics: Notes and problems. Cambridge University Press, Cambridge. UK. 254p.

Cumming, S.G. 2003. Forest and Fire Ecologist, Boreal Ecosystems Research Ltd. Edmonton, Alberta. Personal communication on June 3, 2003.

Cumming, S.G. 2001a. The Lognormal Distribution of Annual Disturbance Rates: Implementation Notes for Spatially Aggregated Dynamic Models. Boreal Ecosystems Research Ltd. Edmonton, Alta. 4p.

Cumming, S.G. 2001b. A Parametric Model of the Fire-Size Distribution. Canadian Journal of Forest Research. 31: 1297-1303.

Cumming, S.G. 2000. Forest Type, Fire Ignition and Fire Frequency in Boreal Mixedwood Forests. SFMN Working Paper, University of Alberta Edmonton, Alta. 24p.

Cumming, S.G. and Wong, C. 2002. Pilot Modelling of Past Fire Dynamics in the IDF. Lignum IFPA Report. 48p.

Davis, R. and Boyland, M. 2003. How Can We Best Model Natural Disturbances Using Atlas and Simfor Software. (draft) Report prepared for the Atlas Simfor Steering Committee. University of British Columbia, Vancouver, BC. 14p.

Davis, R. and Shannon, T. 2003. Examples of Blocking Methods Used in ATLAS Modeling Projects. ATLAS/SIMFOR Project Technical Supplement, 11p. http://www.forestry.ubc.ca/atlas-simfor/extension/reports.html (visited 01/04/2004).

DeLong, S.C. 2003. Regional Ecologist, Ministry of Forests Northern Interior Region, Prince George, BC. Personal Communication on February 5, 2003.

DeLong, S.C. 2002. Natural Disturbance Units of the Prince George Region. Unpublished Report. Ministry of Forests, Prince George, BC. 36p.

DeLong, S.C. 1998. Natural Disturbance Rate and Patch Size Distribution of Forests in Northern British Columbia: Implications for Forest Management. Northwest Science 72: 35-48.

Fall, A. 1999. Iskut-Stikine Fire Model. Prepared for BCMOF, Prince Rupert Forest Region. 8p.

Fall, A., Eng, M., and Sutherland, G. 2001. Simulating Natural Disturbance Dynamics and Evaluating Management Scenarios with the Robson Valley Landscape Model. Prepared for the Robson Valley Forest District Enhanced Forest Management Pilot Project. 58p.

Fall, A. and Fall, J. 2001. A Domain-Specific Language for Models of Landscape Dynamics. Ecological Modelling 141: 1-18.

Fall, J. 1998. Reconstructing the Historical Frequency of Fire: A Simulation Approach to Developing and Testing Methods. MRM Thesis, Simon Fraser University, Vancouver, BC. 93p.

Frelich, L. 2002. Forest Dynamics and Disturbance Regimes: Studies form Temperate Evergreen-Deciduous Forests. Cambridge University Press. Cambridge, UK. 266p.

Gadow, K. v. 2000. Evaluating Risk in Forest Planning Models. Silva Fennica 34(2): 181-191.

Grayston, R. 2003. Zone Protection Officer, Dawson Creek Fire Zone, Dawson Creek, BC. Personal communication on November 24, 2003.

Gustafson, E., Shifley, S., Mladenoff, D., Nimerfro, K. and Hong, S. 2000. Spatial Simulation of Forest Succession and Timber Harvesting using LANDIS. Canadian Journal of Forest Research. 30: 32-43.

Johnson, E. 1992. Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge University Press. Cambridge, UK. 129p.

Johnson, E., Gutsell, S. 1994. Fire Frequency Models, Methods and Interpretations. Advances in Ecological Research, 25: 239-287.

Johnson, E., Miyanishi, K. and Weir, J. 1998. Wildfires in the Western Canadian Boreal Forest: Landscape Patterns and Ecosystem Management. Journal of Vegetation Science 9: 603-610.

Johnson, E., Miyanishi, K. and Weir, J . 1995. Old-growth, Disturbance, and Ecosystem Management. Canadian Journal of Botany 73: 918-926.

Kimmins, J.P. 2001. Future Shock in Forestry. Jubilee Lecture Series, Faculty of Forestry, University of British Columbia, Vancouver, Canada. 20p.

Kimmins, J.P. 1998. Respect for Nature: An Essential Foundation for Sustainable Forest Management. *In* D'Eon, R.G., Johnson, J., and Ferguson, E.A. (editors). Ecosystem Management of Forested Landscapes. UBC Press. Vancouver, Canada. pp 3-24

Kimmins, J.P. 1990. Modelling the Sustainability of Forest Production and Yield for a Changing and Uncertain Future. For. Chron. 66: 271-280.

Kimmins, J.P. 1987. Forest Ecology. Macmillan, New York. 531p.

Kimmins, J.P., Mailly, D. and Seely, B., 1999. Modelling Forest Ecosystem Net Primary Production: The Hybrid Simulation Approach used in FORECAST. Ecological Modelling. 122: 195-224.

Kimmins, J.P., and Sollins, P. 1989. Modelling Long-Term Forest Productivity. *In* Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. Timber Press, Portland, Oregon. pp. 202-220

Kurz, W. 2000. Habitat Patterns in Forested Landscapes: Management Practices and the Uncertainty Associated with Natural Disturbances. Computers and Electronics in Agriculture. 27: 243-262.

Lessard, R. 1998. Spatial and Temporal Dynamics of Forest Disturbance: A Stochastic Simulation Model. MSc. Thesis. Univesity of British Columbia, Vancouver, BC. 59p.

Marshall, P. 1985. Risk and Uncertainty in the Analysis of Timber Supply. Forest Economics and Policy Analysis Project. Report 85-12. 22p.

Martell, D. 1994. The Impact of Fire on Timber Supply in Ontario. Forestry Chronicle. 70(2): 164-173.

Nelson, J. 2003a. Forest-Level Models and Challenges for their Successful Application. Canadian Journal of Forest Research. 33: 422-429.

Nelson, J. 2003b. Forest Planning Studio – ATLAS Program Reference Manual Version 6. Faculty of Forestry, University of British Columbia, Vancouver, BC. 104p. http://www.forestry.ubc.ca/atlas-simfor/extension/docs.html#Atlas (visited 01/04/2004).

Nelson, J. 2001. Assessment of Harvest Blocks Generated for Operational Polygons and Forest-cover Polygons in Tactical and Strategic Planning. Canadian Journal of Forest Research. 31: 682-693.

Nelson, J. 2000. The Mechanics of Adjacency. ATLAS-SIMFOR Project Extension Report 1, University of British Columbia, Vancouver BC. 8p. http://www.forestry.ubc.ca/atlas-simfor/extension/reports.html (visited 01/04/2004).

Nelson, J. and Davis, R. 2002. Is Detail Impeding Strategic Thinking? A Critical Look at Spatial Detail in Forest Estate Models. ATLAS/SIMFOR Project Extension Report, 31 pp. http://www.forestry.ubc.ca/atlas-simfor/extension/reports.html (visited 01/04/2004).

Olivotto, G. 1999. Landscape Disturbance and Harvest Scheduling. Unpublished Report. Research Branch. BC Ministry of Forests, Smithers, BC. 4p.

Powers, D, and Xie, Y. 2000. Statistical Methods for Categorical Data Analysis. Academic Press, San Diego, USA. 305p.

Reed, W. and Errico, D. 1986. Optimal Harvest Scheduling at the Forest Level in the Presence of the Risk of Fire. Canadian Journal of Forest Research, 16: 266-278.

Ripley, B. 1987. Stochastic Simulation. John Wiley and Sons, New York. 237p.

Rosen, D. 2002. Forest Inventory Specialist, Canadian Forest Products Ltd., Chetwynd, BC. Personal communication on July 26, 2002.

Seely, B. 2003. Development of the Stand Attribute Database for use in the Strategic Analysis of Landscape Level Management Alternatives in Block 4 of TFL 48. Unpublished report. University of British Columbia, Vancouver, BC. 11p.

Seely, B., Nelson, J., Wells, R., Peter, B., Meitner, M., Anderson, A., Harshaw, H., Sheppard, S., Bunnell, F., Kimmins, H. and Harris, D. In press. The Application of a Hierarchical, Decision-Support System to Evaluate Multi-Objective Forest Management Strategies: A Case Study in Northeastern British Columbia, Canada. Forest Ecology and Management. 48p.

Stocks, B. 1991. The Extent and Impact of Forest Fires in Northern Circumpolar Countries. *In*: Global Biomass Burning: Atmospheric, climatic and Biospheric Implications. Levine, J. (ed.) MIT Press, Cambridge, Mass. pp. 197-202.

Taudin-Chabot, P. 2003. Untitled Lecture. *In:* The Fires of Summer 2003: A Reflection on the Changing Urban Interface: What Happened, Why and...What Next?. UBC Faculty of Forestry Public Lecture. 19 November 2003.

van Wagner, C. 1983. Simulating the Effect of Forest Fire on Long-term Annual Timber Supply. Canadian Journal of Forest Research. 13:451-457.

Weber, G. and Stocks, B. 1998. Forest Fires and Sustainability in the Boreal Forests of Canada. Ambio 27-7: 545-550

Weintraub, A. and Abramovich, A. 1995. Analysis of Uncertainty of Future Timber Yields in Forest Management. Forest Science. 41-2: 217-234.

APPENDIX 1

KEY TO SCENARIOS AND RUN NUMBERS

Appendix 1 – Key to Scenarios and Run Numbers

A total of 15,003 FPS-ATLAS runs were conducted for this thesis. Run numbers refer to the landscape, scenario, and run number within the scenario. Large batches of runs used to determine harvest rates had fewer output files to minimize processing time and disk space, and are denoted with an 'h'. Runs used to examine landscape statistics or cash-flow with detailed output files are denoted with a 'd'. Runs used to determine availability at specific periods are denoted with an 'a'.

Grid Scenarios

Growth Only
Run 1.1.1d (one run with detailed output)
Growth and Disturbance
Runs 1.2.1d – 1.2.50d (50 runs with detailed output)
Growth and Harvest
Run 1.3.1a – 1.3.40a (one test of availability for 40 periods = 40 runs)
Run 1.3.1d (one run with detailed output)
Growth, Disturbance and Harvest
Runs 1.4.1h – 1.4.900h (10 runs at 90 harvest targets = 900 runs)
Runs 1.4.1a – 1.4.1200a (30 tests of availability for 40 periods = 1200 runs)
Runs 1.4.1d – 1.4.10d (10 runs with detailed output at the chosen harvest target)
Growth, Disturbance and Harvest (no salvage)
Runs 1.5.1h – 1.5.700h (10 runs at 70 harvest targets = 700 runs)
Growth, Disturbance and Harvest (Alpha = 0)
Runs 1.6.1h – 1.6.700h (10 runs at 70 harvest targets = 700 runs)
Growth, Disturbance and Harvest (Alpha = 0.1)
Runs 1.7.1h – 1.7.700h (10 runs at 70 harvest targets = 700 runs)
Growth, Disturbance and Harvest (Alpha = 0.25)
Runs 1.8.1h – 1.8.700h (10 runs at 70 harvest targets = 700 runs)
Growth, Disturbance and Harvest (Alpha = 0.5)
Runs 1.9.1h – 1.9.700h (10 runs at 70 harvest targets = 700 runs)
Growth, Disturbance and Harvest (Alpha = 1.0)
Runs 1.10.1h – 1.10.700h (10 runs at 70 harvest targets = 700 runs)
Growth, Disturbance and Harvest (Harvest Regime 1 only)
Runs 1.11.1h – 1.11.300h (10 runs at 30 harvest targets = 300 runs)
Growth, Disturbance and Harvest (Harvest Regime 2 only)
Runs 1.12.1h – 1.12.700h (10 runs at 70 harvest targets = 700 runs)
Growth, Disturbance and Harvest (Large Sample)
Runs 1.13.1h – 1.13.4500h (50 runs at 90 harvest targets = 4500 runs)

TFL 48 Block 4 Scenarios

Growth and Harvest
Run 2.1.1d (one run with detailed output)
Growth and Historical Disturbance
Run 2.2.1a – 2.2.30a (one test of availability for 30 periods = 30 runs)
Runs 2.2.1d – 2.2.10d (10 runs with detailed output)
Growth, Historical Disturbance and Harvest
Runs 2.3.1h – 2.3.700h (10 runs at 70 harvest targets = 700 runs)
Runs 2.3.1a – 2.3.300a (10 tests of availability for 30 periods = 300 runs)
Runs 2.3.1d – 2.3.10d (10 runs with detailed output at the chosen harvest target)
Growth, Suppressed Disturbance and Harvest
Runs 2.4.1h – 2.4.700h (10 runs at 70 harvest targets = 700 runs)
Runs 2.4.1a – 2.4.300a (10 tests of availability for 30 periods = 300 runs)
Runs 2.4.1d – 2.4.10d (10 runs with detailed output at the chosen harvest target)
Growth, Conditionally Suppressed Disturbance and Harvest
Runs 2.5.1h – 2.5.700h (10 runs at 70 harvest targets = 700 runs)
Runs 2.5.1a – 2.5.300a (10 tests of availability for 30 periods = 300 runs)
Runs 2.5.1d – 2.5.10d (10 runs with detailed output at the chosen harvest target)
Growth, Conditionally Suppressed Disturbance and Harvest (Risk=0.5)
Runs 2.6.1d – 2.6.10d (10 runs with detailed output at the chosen harvest target)
Growth, Conditionally Suppressed Disturbance and Harvest: (Risk=0.9)
Runs 2.7.1d – 2.7.10d (10 runs with detailed output at the chosen harvest target)
Growth, Conditionally Suppressed Disturbance and Harvest: (Risk=1.0)
Runs 2.8.1d – 2.8.10d (10 runs with detailed output at the chosen harvest target)