University of Alberta

Measuring and approximating the effects of forest fires on timber supply in Alberta

by

Richard Dean Simpson ©

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Abstract

The cost of reduced harvest levels from land base removals and stochastic events, such as forest fires, can theoretically be measured using shadow prices. It was found that if a land base removal event caused the area to be permanently removed from the productive land base that shadow prices accurately estimated the cost of the event. When the area was assumed to regenerate shadow prices were less effective at estimating the cost of the events. Sequential re-planning was used to test the effect of salvage policies on future timber supply. It was shown that regenerating the post-fire land base stabilized the harvest level through time, but does not significantly increase harvest level. Counting the salvage volume against the AAC increased the benefits to society from the forest while decreasing the benefits to the tenure holder. This increase was caused by decreasing the portion of the burnt area salvaged; increasing habitat for species that require burnt areas for habitat. As well as a decrease in green wood harvest, which increases the amount of old growth forest on the land base.

Acknowledgements

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Chapter 1.

Introduction

1.1 Using shadow prices for estimating the cost of land base removals.

Linear programming (LP)-based forest planning models are commonly used in Alberta to estimate the level of harvest that can be sustained from a defined land base into perpetuity. LP-based forest planning models normally do not take into account stochastic or unpredictable events. These events include forest fires and land removals for industrial or public uses. When these events occur on the land base after the initial planning phase they change the optimal solution of the model. Independent of the event size, changing the LP-based forest planning model to include unscheduled events is a difficult and time consuming process, requiring trained geographic information system specialists and resource analysts. When unscheduled events occur on the land base changing either the harvest level or land base by more than 2.5%, the LP-based forest planning model must be updated or recreated (Alberta Sustainable Resource Development, 2002). This update involves identifying the area(s) affected by the event(s), removing (or modifying) the affected area from the LP-based forest planning model and re-optimizing the updated model. This method of calculating the cost of a land base removal is referred to as the "remove and recalculate" approach by Armstrong and Cumming (2003). The change to the objective function value is referred to as the cost of the land base removal.

There has been research on identifying alternate means of calculating the cost of land base removals or changes using shadow prices. Shadow prices represent the amount the objective function value would change if the right hand side of a constraint was slackened or tightened by one unit. Shadow prices are theoretically only valid for small changes to the right hand side of a constraint. In many cases land base removals cause large changes to the right hand side of many constraints. Therefore, research is needed to test whether the changes to right hand side of the constraints caused by land base removals change the shadow price values to a degree where shadow prices no longer accurately approximate the change to the constraint value. Armstrong and Cumming (2003) used shadow prices to approximate the cost of simulated fire years on a land base in northeastern Alberta. They created a simple LP-based forest planning model which was initially optimized without fire years included. They then individually incorporated fire years using the "remove and recalculate approach to measure the cost of these fire years under different scenarios. They then used area weighted shadow prices calculations to approximate the cost of these simulated fire years. Under a range of fire sizes they found that shadow price approximations closely estimated the cost of these fire years. Shadow prices have also been used to approximate the cost of removing townships from a land base in northeastern Alberta (R. Stronach and K. Peck, Alberta Sustainable Resource Development. pers. comm.). This research found that under the formulations used shadow prices did not accurately approximate the cost of removing townships.

The ability to use shadow prices to approximate the cost of land base removals would have a number of benefits. Firstly, the ability to approximate the effect a land base removal has on the annual allowable cut (AAC), and subsequently the ability to approximate whether the AAC must be recalculated based on the government trigger. Secondly companies could proactively approximate the effect of land base removals such as roads and pipelines on their AAC to minimize their effect. Thirdly, shadow price approximations are cost effective as they do not require trained geographic information system analysts and resource analysts to approximate the cost of a land base removals.

The purpose of chapter 2 will be to test whether shadow prices can be used in realistic scenarios within Alberta to approximate the cost of land base removals. Full scale LP-based forest planning models will be used to approximate the cost of real fires that occurred in Alberta to further the study by Armstrong and Cumming (2003). Different regeneration assumptions and constraint sets will be analyzed to test the robustness of this method. The ability of shadow prices to approximate the cost of land base removals, in the form of townships, will also be tested on a reduced scale.

1.2 Testing the effects of salvage policy on long term harvest level.

The Alberta government allocates harvest to companies through different means - the majority of the harvest is allocated through Forest Management Agreements (FMA). An FMA area represents a defined area where a company has rights to manage for timber harvest (Alberta Sustainable Resource Development, 1996). Extensive planning must be completed prior to harvest occurring, including the determination of an AAC. Companies holding FMAs have rights to harvest timber from the land base, and the rights to access this timber. Often there are other industrial activities occurring on the same land bases, including oil and gas exploration, and agricultural activities, particularly grazing. Along with other industrial activities, there are natural processes occurring such as fire and forest succession. With all of the activities and processes occurring on a limited land base the sustainability of these areas is uncertain.

Other industrial activities and natural processes occur in unpredictable manners and are therefore often dealt with retroactively by forest companies. Other industries, especially the oil and gas industry, plan their activities on a much shorter time scale than the forest industry making it difficult for FMA holders to incorporate other industrial activities into their long term plans. Predicting the size and location of natural processes such as forest fires is very difficult as forest fires are stochastic events. Forest fires conflict directly with timber harvesting activities as they both consume timber. This is especially true for fire adapted coniferous forests which have higher burn probabilities than deciduous forests (Cumming, 2001). However forest fires do not destroy the utilized portion of the tress and the burnt timber is still harvestable for a period of some years post-fire, commonly two (Watson and Potter, 2004).

In Alberta, post-fire areas and volume salvaged from these areas have been dealt with in different manners (Alberta Sustainable Resource Development, 2002). Historically it has not been the responsibility of tenure holders to regenerate these post-fire areas. Since the post-fire areas were not regenerated they were removed from the operational land base and AAC determinations until surveys show they were sufficiently restocked. More recently companies have regenerated these post-fire areas, and retained them in their AAC determinations. Historically the volume salvaged from post-fire areas was not counted against a tenure holder's AAC. Tenure holders were therefore able to harvest their entire AAC in green wood, and additionally harvest any salvageable volume from post-fire areas. It was suspected that the manner in which post-fire areas and volume salvaged from these areas were dealt with would directly affect the long term harvest levels achievable from the land base.

The purpose of chapter 3 is to estimate the effects of different salvage policies on long term harvest levels. Sequential re-planning simulations are created under a number of salvage policies to estimate the effect salvage policy had on harvest level. These sequential re-planning simulations were completed by determining an the AAC and subsequently spatially allocating this AAC onto the land base for 5 years. The forest area was then aged, and simulated fires were place on the land base and the forest was aged by 5 years. A new AAC was determined based on the new land base state, and this new AAC was spatially allocated onto the land base. Fires were then again incorporated and the forest area was again aged. This process was repeated for 100 years and the change in harvest from the land base was tracked. This process was completed under different salvage policies to determine the effect of the different policy on the harvest level achievable from the land base.

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Chapter 2.

Approximating the cost of land base removals using shadow prices

2.1 Introduction

About ninety percent of forested lands in Alberta are provincially owned (Canadian Council of Forest Ministers, 2004). Much of this area has been allocated to private companies for management of the timber resource. Companies with rights to harvest timber from these provincially owned lands must follow government guidelines for the planning and management of these lands. Forest management planning involves developing future plans based on the current land base information. One of the steps in the planning process is an analysis of timber supply using forest planning models. This step requires the companies to estimate the level of harvest that is sustainable from the land base given the current land base information and planned activities.

Forest planning models, also known as timber supply models, are tools used by government and industry to help decide what level of harvest should be undertaken for a designated area. In Alberta, companies create their own forest planning models that are subject to approval by the government prior to implementation. Forest planning models use information available for a particular area to find the optimal solution to a mathematical representation of the planning problem subject to user defined constraints (Davis *et al.* 2001). The optimal solution represents the maximum harvest possible from the land base subject to the user defined constraints. These problems are often solved using linear programming, but they can also be solved using simulations. The government specifies constraints and processes that must be completed by companies in the creation of the forest planning model, though companies can add other constraints if desired (Alberta Sustainable Resource Development, 1998a). These constraints and processes specified by the government include public involvement, identification of long run goals, and sustained yield management.

When an LP-based forest planning model is optimized there are usually outputs additional to the optimal solution. One output that most linear programming solvers produce while solving a linear programming problem is shadow prices. Shadow prices represent the value that one unit change on the right hand side of a constraint will have on the value of the objective function. All constraints within a linear programming problem have associated shadow prices. The units of shadow prices are the same as the units of the objective function per unit change of the constraint (Davis et al., 2001). The starting inventory of a land base is constrained within LP-based forest planning models. The starting inventory constraint set states the amount of area in each forest type present in the starting inventory; therefore shadow prices are available for the entire starting inventory. The starting inventory constraint set gives the value of a single unit of area for each of the different forest types on the land base - summing these values, weighted by area, gives the value of the objective function. Shadow prices are theoretically valid only for small changes to the constraint values, as large changes to the constraint values could change the binding situation of the optimal solution, therefore changing the shadow price values.

When the land base changes from what is represented in the original model, the original optimal solution is no longer valid. Land base removals are anything that modify the initial information used for modeling, including removing areas from the land base or changing the state of (a) stand(s). These land base removals include forest fires, new unplanned road constructions, well site removals, or new protected area creations. Since these land base removals are unplanned, and unpredictable, they are not usually incorporated into forest planning models. Therefore land base removals are usually dealt with in a reactive manner. When there is a 2.5% or greater change to either the area from which a company has rights to harvest timber from, or the Annual Allowable Cut (AAC), the company must recreate or update their forest planning model (Alberta Sustainable Resource Development, 2002). AAC refers to the amount of timber a company can annually harvest from a designated area. Arguably the most stochastic land base removals are forest fires. Fire plays a critical role in shaping the structure of the boreal forest (Johnson, 1992).Forest fires start in unpredictable locations and spread depending on many characteristics, such as weather conditions, vegetation, and topographic characteristics (Hargrove *et al.*, 2000). The stochastic start locations and spread characteristics of forest fire create unique fire sizes and shapes.

Armstrong and Cumming (2003) presented a method of approximating the cost of forest fire years using shadow prices from the starting inventory generated by an LP-based forest planning model. The cost of fire years in their study represented the change to the objective function value, which was expressed as harvest volume in the first decade. The shadow price approximations were calculated by summing the area weighted shadow prices from the starting inventory constraint set of the affected area. The method's accuracy was tested by comparing the "remove and recalculate" cost to the shadow price approximations. The "remove and recalculate" cost of the fire years was calculated by removing or modifying the affected areas in the LP-based forest planning model and subsequently resolving the model. Armstrong and Cumming claimed that based on the results of their study, which used 10,000 simulated fire years that reduced the harvest level by up to 40% from the pre-fire harvest level, that shadow price approximations were an effective method of approximating the cost of forest fires. They showed that when the land base was removed from production post-disturbance, the ratio of the "remove and recalculate" cost to the shadow price approximation was between 0.98 and 1. When they assumed the land base to regenerate post-fire, the ratios were between 0.61 and 1. They stated this method was very accurate at approximating the cost of fires over a range of fire sizes and model formulations. Armstrong and Cumming (2003) conducted their study on one study area using simulated fires and a simplified LP-based forest planning model. They recommended using real fires and full scale LP-based forest planning models to determine whether this method was more generally applicable. Theoretically using shadow prices to approximate land base removals may not be accurate as the shadow prices from the starting inventory may not be valid for large changes to the land base that occur when large fire occur.

Research has also been completed using shadow prices to approximate the cost of township removals from a land base in northeastern Alberta (R. Stronach and K. Peck, Alberta Sustainable Resource Development. pers. comm.). The results from this research showed varying levels of accuracy when using shadow prices to approximate the cost of land base removals. With the conflicting results between this research and that of Armstrong and Cumming (2003) there were uncertainties about differences in methods or land base sensitive results. These differences could be reconciled by approximating the cost of both fires and township removals on the same land base.

Woodstock is a program commonly used for creating LP-based forest planning models (Remsoft, 2003a) and was used in this study. Woodstock uses unique techniques for classifying areas. Initially themes must be defined – themes represent a characteristic by which a stand can be classified; such as density, natural subregion, species, site class, or other characteristic which is important to the analysis. The combination of theme characteristics representing a stand is called a development type and does not include age information. When age information is combined with development types they identify development type classes.

The ability to use shadow prices to approximate the cost of land base removals would have a number of benefits. Firstly, the ability to approximate the effect a land base removal has on the annual allowable cut (AAC), and subsequently the ability to approximate whether the AAC must be recalculated based on the government trigger. Secondly companies could proactively approximate the effect of land base removals such as roads and pipelines on their AAC to minimize their effect. Thirdly, shadow price approximations are cost effective as they do not require trained geographic information system analysts and resource analysts to approximate the cost of a land base removals.

Two major fires that occurred in Alberta in the last decade are the House River fire and the Dogrib fire. The House River fire (LWF-031-2002) occurred during the summer of 2002, partially within forest management unit (FMU) L1 in the Forest Management Agreement area (FMA) of Alberta-Pacific Forest Industries Inc. (Alberta Sustainable Resource Development, 2004). The fire burned approximately 11% of the area within FMU L1 - this accounted for only 15% of the total fire area. The Dogrib fire (RWF-085-2001) occurred in the fall of 2001, partially within the Sunpine Forest

Products Ltd. FMA (Alberta Sustainable Resource Development, 2004). The fire burnt approximately 2% of Sunpine Forest Products' FMA area (Alberta Sustainable Resource Development, 2004) - this accounted for approximately 69% of the total fire area.

This study had multiple objectives: first to evaluate the usefulness and accuracy of using shadow prices to approximate the change in harvest from fires and land base removals using real forest inventory information, yield tables, and LP-based forest planning models. This study used methods similar to Armstrong and Cumming (2003), though it was expanded to include full-scale LP-based forest planning models and real fires. The second objective was to obtain digital forest inventory information and LP-based forest planning models and combine them to be able to rapidly and accurately approximate the cost of forest fires using shadow prices, given that the fire area is removed from production post-fire. The third objective was to test the applicability of this method if the land base was assumed to regenerate post-fire, and to test the effect of differing constraints on the model's accuracy. The final objective was to examine the accuracy of this method to approximate the cost of township removals.

In the remainder of this chapter first there will be a description of the study areas, followed by a thorough discussion of the LP-based forest planning models used. Then a description of the methods used to test the accuracy of the shadow price approximations will be shown, and subsequently described and discussed.

2.2 Study Areas

The study areas that will be used are Alberta-Pacific's FMU L1 in northeastern Alberta, and Sunpine Forest Products' FMA in southwestern Alberta (Figure 2.1). The digital forest inventories and LP-based forest planning models are available from both

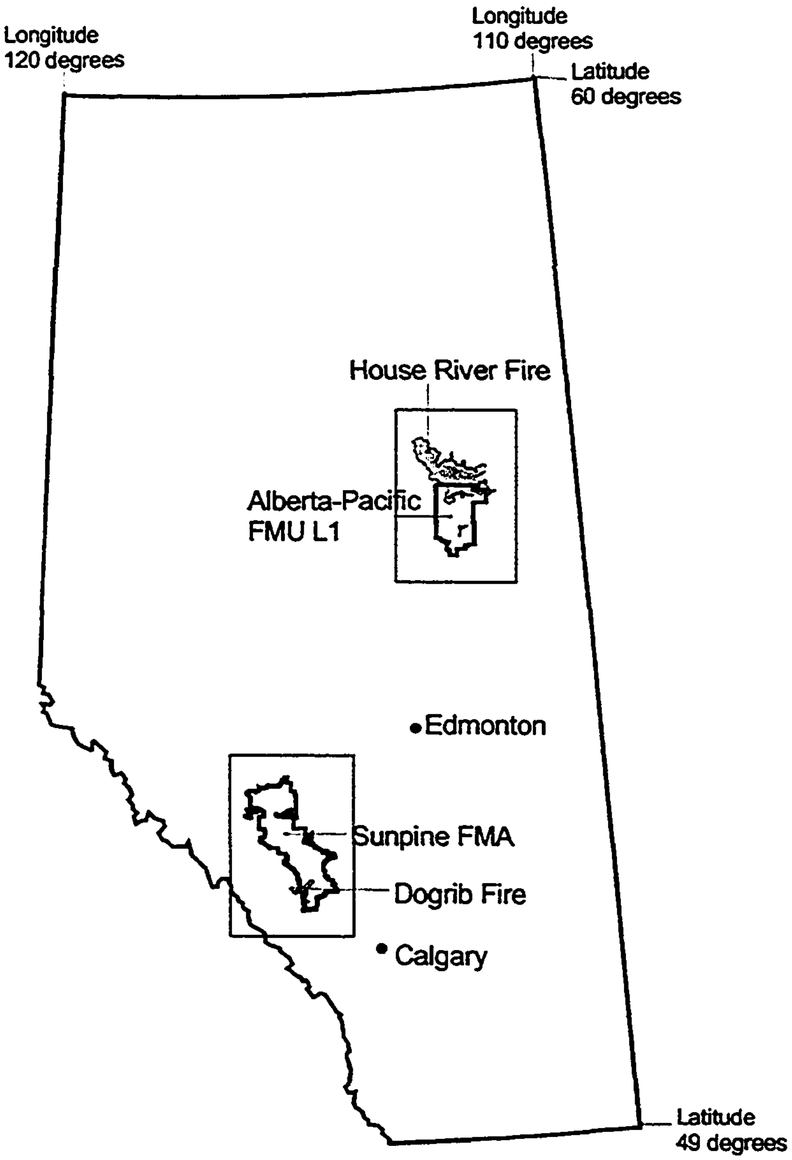

Figure 2.1. Map of Alberta showing the locations of Alberta-Pacific's FMU L1 and Sunpine's FMA; as well as the locations of the House River fire and the Dogrib fire which were used in this study.

companies. Alberta-Pacific's FMU L1 is comprised of 334,000 ha of land, of which only 143,000 ha are operational (all areas are pre-fire unless otherwise stated), meaning that only 43% of the land base is managed for timber production. The main tree species in FMU L1 are aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), and black spruce (*Picea mariana* (Mill.) B.S.P.).

In addition to basic Alberta Vegetation Inventory (AVI) information, administrative data is also available for the study area (Alberta Environmental Protection, 1991). This administrative data included administrative boundaries, ecological zones, and land base exclusions, both subjective and administrative. The information is broken into a hierarchical classification system of themes (Table 2.1), based on the Alberta-Pacific Land Base Determination Document, Version 2 (Timberline Forest Inventory Consultants Ltd., 2002).

There was information in the model as obtained from Alberta-Pacific that did not appear in the starting inventory. Some of this information was specific to other FMUs in which Alberta-Pacific has rights to harvest. Other information that did not occur in the starting inventory was created through transitions later in the model. Each polygon could take 1 of 109 billion different possible development types classes. However only 19,000 development type classes are represented in the starting inventory of the forest. There are 22 yield tables within the Alberta-Pacific LP-based forest planning model, based on the cover-type theme.

The Alberta-Pacific land base has a history of large stand-replacing fires (Cumming, 2001). The starting inventory age class distribution of FMU L1 is far from

Table 2.1. The theme information from the Alberta-Pacific LP-based forest planning model; showing all theme choices available as well as types that appear in the starting inventory.

Alberta-Pacific					
Theme	Classification	options	Theme	Classification	options
1	Natural Sub-Region	7	6	Density	5
	- Boreal Highlands			- 'A' density *	
	- Central Mixedwood *			- 'B' density *	
	- Dry Mixedwood *			- 'C' density *	
	- Sub-Arctic			- 'D' density *	
	- Athabasca Plain			- Non forested or cover *	
	- Lower Foothills		7	Land base exclusions	12
	- Upper Foothills			- Liege river protected area	
2	FMU	5		- Provincial parks *	
	- L1a *			- Aboriginal reserves	
	- L1b *			- Ecological reserves	
	- L1c *			- Deciduous river breaks	
	- L1d *			- Coniferous river breaks	
	- L1e *			- Boreal sites	
3	Land base	3		- Permanent sample plot buffers *	
	- Coniferous land base *			- No exclusion *	
	- Deciduous land base *			- Grazing reserves *	
	- Undetermined land base *			- Outside FMA *	
4	Cover Type	30		- Protected notation *	
	- Aw-comp *		8	Land base exclusions	16
	- Aw-S-O			- Fire *	
	- Aw -S-C-S			- Oil and gas *	
	- Aw-S-C-N			- Slope greater than 45% *	
	- Aw-Pj			- Non-forested vegetated *	
	- AwS-S *			- Non-forested disturbance *	
	- AwS-N			- Non-forested clear-cuts *	
	- MxPj *			- Anthropogenic non-vegetated *	
	- Saw-S *			- Anthropogenic vegetated *	
	- Saw-N			- Naturally non-vegetated *	
	- Lt *			- Unproductive index *	
	- Sw-O *			- Unproductive stand density *	
	- Sw-C-FM *			- Larch component *	
	- Sw-C-G			- Unproductive site index *	
	- Sb-O *			- Isolated stands *	
	- Sb-C-FM *			- Caribou habitat *	
	- Sb-C-G *			- No exclusion *	
	- Pj-O-C-FM *		9	Land base exclusions	5
	- Pj-C-G *			- Water buffer *	
	- Aw-U-FM *			- Deciduous within 15m of intermittent	
	- Aw-U-G *			- No buffer *	
	- Aw-S-U-S *			- Harvestable buffer	
	- Aw-S-U-N			- Restricted harvesting	
	- Naturally non-vegetated *		10	Planning unit	129
	- Non-forested vegetated *			- 067254 *	
	- Anthropogenic vegetated			- 068134 *	
	- Anthropogenic non-vegetated			- ... *	
	- Non-forested disturbances *			- 099074 *	
	- Non-forested clear-cuts *		11	Harvest season	2
	- Area outside the FMA *			- Summer *	
5	State	7		- Winter *	
	- 'A' density stands *		12	Land base	2
	- 'A' density in second rotation			- FMA Land base *	
	- Delayed state *			- Non-FMA land base *	
	- Natural state *		13	Township status	2
	- Non successful regeneration			- Open *	
	- Regeneration state *			- Closed	
	- No status *		Possible development type		109,226,880,000

* appear in original starting inventory data set

the classical notion of a 'normal forest', with a high percentage of the forest area being in older (70+ years) age classes (Figure 2.2). Recent harvest activities and forest fires have increased the amount of area in young age classes.

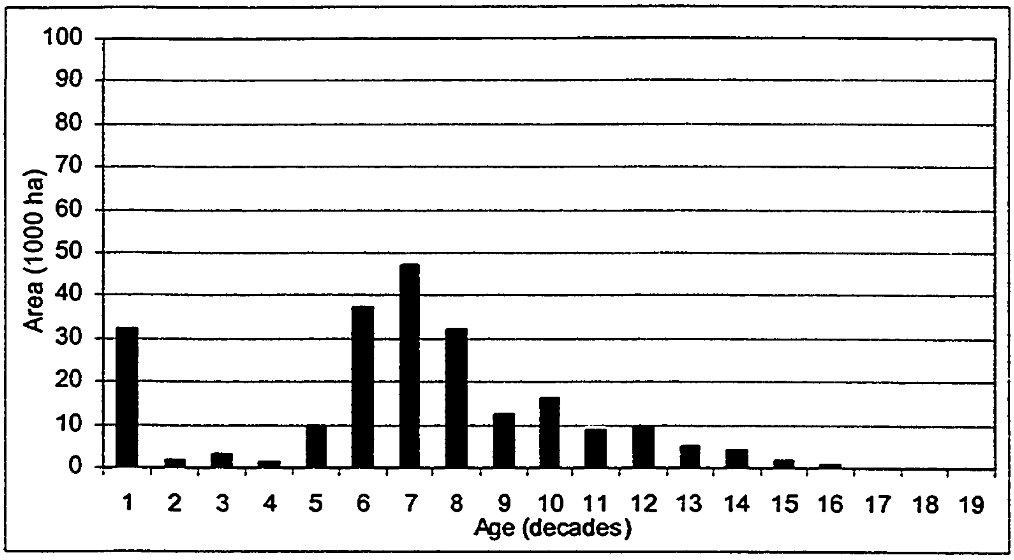

Figure 2.2. Starting inventory age class distribution of FMU L1 in 10 year periods.

The Sunpine FMA area comprises a total of 579,000 ha, 414,000 ha of which are operational: 73% of the land base is managed for timber production. The main tree species in Sunpine's FMA are lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.), white spruce, aspen, and black spruce. The information obtained for the Sunpine land base is similar to the information obtained for the Alberta-Pacific land base. The Sunpine model contained fewer themes than the Alberta-Pacific model - only 7 as opposed to 13 (Table 2.2). These themes each contain a similar number of options, which means that approximately 3 million development type classes were possible in the model, though only 15,000 occurred in the starting inventory. The 21 yield curves within this model are designated based on the species type, natural subregion, stand density, and timber productivity rating.

Table 2.2. The theme information from the Sunpine LP-based forest planning model; showing all theme choices available.

Sunpine								
Theme	Classification	Options	Theme	Classification	Options	Theme	Classification	Options
1	SYU	2		- Trout Creek			- Pine	
	- FMU R10			- Two Dam Creek			- White spruce/ Fir	
	- FMU R11			- Upper Cripple Creek			- Black spruce/larch	21
2	Compartment	98		- Upper Lick Creek			- Deciduous	
	- Alford Creek			- Upper Tay River		6	Yield Type	
	- CTLB080009			- Bluehill West			- Non forested	
	- Baptiste River			- Wildhorse Creek			- A or B density/Coniferous/	
	- Bluehill			- Williams Creek			Fair site/ Sub Alpine	
	- Bridgeland Creek			- Willson Creek			or Upper foothills	
	- Clearwater River			- Yara Creek			- A or B density/ Coniferous/	
	- Colt Creek			- CTLB060021			Medium or Good site/	
	- Contingency			- CTLR070057			Sub Alpine or Upper foothills	
	- Cutoff Creek			- Weyerhaeuser Quota			- C or D density/ Coniferous/	
	- Dutch Creek			- Rocky Wood Preservers			Fair site/ Sub Alpine or	
	- East Ram River			- CTLR070047			Upper foothills	
	- Elk Creek			- R7-Q4			- C or D density/ Coniferous/	
	- Falls Creek			- R9-MTU			Medium or Good site/ Sub	
	- Gap Creek			- CTLR050029			Alpine or Upper foothills	
	- Gap Lake			- CTLR050027			- A or B density/ Coniferous/	
	- Gloomy Creek			- CTLR070058			Fair site/ Lower Foothills	
	- Haven Creek			- B8Q11CP2			- A or B density/ Coniferous/	
	- Highway 11			- C139 None			Medium or Good site/	
	- Highway 752			- C140 Grazing Lease			Lower Foothills	
	- James Pass			- C142 Grazing Lease			- C or D density/ Coniferous/	
	- James River			- C144 Grazing Lease			Fair site/ Lower Foothills	
	- Jock Lake			- Old R05 and			- C or D density/ Coniferous/	
	- Lewis Creek			- Alexo			Medium or Good site/	
	- Lick Creek			- C155 Grazing Lease			Lower Foothills	
	- Limestone Creek			- R8 WEST			- A or B density/ Mixedwood/	
	- Lower Cripple Creek			- C171 None			Fair site/ Sub Alpine or	
	- Lower Pinto Creek			- C192 None			Upper foothills	
	- Lynx Creek			- R9 West			- A or B density/ Mixedwood/	
	- Marble Mountain			- Old R09 and			Medium or Good site/	
	- MacGregor Lake			- B6 WEST			Sub Alpine or Upper foothills	
	- Meadows Creek			- C233 None			- C or D density/ Mixedwood/	
	- North Ram River			- C227 Grazing Lease			Fair site/ Sub Alpine or	
	- Otter Creek			- C228 Grazing Lease			Upper foothills	
	- Pineneedle Creek			- C232 Grazing Lease			- C or D density/ Mixedwood/	
	- Pinto Creek		3	Landbase	8		Medium or Good site/	
	- Prairie Creek			- Non-forested			Sub Alpine or Upper foothills	
	- R5-Q8			- Coniferous			- A or B density/ Mixedwood/	
	- CTLR050028			- Deciduous			Fair site/ Lower Foothills	
	- R7-MTU			- Coniferous - mixedwood			- A or B density/ Mixedwood/	
	- R9-Q5			- Coniferous - deciduous			Medium or Good site/	
	- R9-Q7			overstory with C, CD, DC,			Lower Foothills	
	- Radiant Creek			understory(B,C,D density)			- C or D density/ Mixedwood/	
	- Ram Mountain			- Deciduous - deciduous			Fair site/ Lower Foothills	
	- Rapid Creek			overstorey with C, CD,DC,			- C or D density/ Mixedwood/	
	- Raven River			understory (A density)			Medium or Good site/	
	- Red Deer River			- Coniferous cutover			Lower Foothills	
	- Rocky Creek			- Deciduous cutover			- A or B density/ Deciduous/	
	- Rough Creek		4	Deletions	11		Fair Site/ Lower Foothills	
	- Saskatchewan River			- None			or Upper Foothills	
	- Shunda Creek			- Non-Forested			- A or B density/ Deciduous/	
	- Skunk Creek			- Status			Medium or Good Site/ Lower	
	- South Creek			- Prime protection			Foothills or Upper Foothills	
	- South James River			- Slope			- C or D density/ Deciduous/	
	- South Ram River			- Watercourse buffer			Fair Site/ Lower Foothills	
	- Stoney Creek			- Access buffer			or Upper Foothills	
	- Swan Creek			- Subjective			- C or D density/ Deciduous/	
	- Swan Lake			- West			Medium or Good Site/ Lower	
	- Tawadina Creek			- Inaccessible			Foothills or Upper Foothills	
	- Tay River			- Horizontal		7	Stand Status	2
	- Teepee Creek		5	Leading Species	5		- Standing Timber	
	- The Forks			- None			- Regenerated Timber	
							Possible development types	3622080

The Sunpine FMA is part of the foothills forest area of Alberta (Alberta Sustainable Resource Development, 1996) which has a history of fire that has drastically changed the landscape (Andison, 2003). The Sunpine FMA area has a starting age class distribution in which the majority of the stands are between 70 and 130 years old. The distribution exhibits a large tail into the older age classes (Figure 2.3).

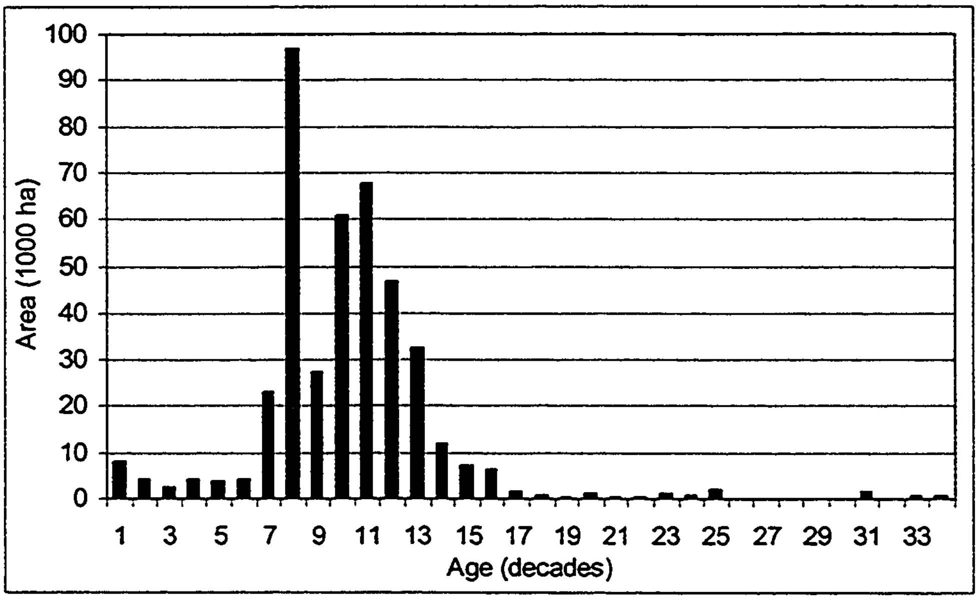

Figure 2.3. Starting inventory age class distribution of the Sunpine FMA area in 10 year periods.

2.3 Models

The LP-based forest planning models used in this study were obtained from Alberta-Pacific and Sunpine. They were kept as close to their original forms as possible to test the applicability of shadow price approximations to measure for the cost of land base removals using full-scale LP-based forest planning models. The models were changed to ensure an exact join between the spatial and aspatial data sets and to allow a comparison of results with previous studies. Both of these models follow the guidelines set out by the Alberta government for the creation of forest planning models (Alberta Sustainable Resource Development, 1996, 1998a, 1998b).

The objective function in both the Alberta-Pacific and Sunpine models was the maximization of the total volume, both softwood and hardwood, harvested from the land base over two rotations. The constraints placed on the models were varied creating four different cases (Table 2.3) which were analyzed in this study. An even flow constraint was varied between a separate constraint on the softwood and hardwood and a combined constraint of the softwood and hardwood. An ending inventory constraint was placed on the model in two of the cases, where the growing stock on the land base could not decline over the last half of the planning horizon. These constraints are included to ensure that the timber harvest followed the sustained yield principle. Both models were created and run in the Woodstock forest modeling system (Remsoft, 2003a), and optimized using XA Linear Optimizer System (Sunset Software Technology, 2003).

Table 2.3. Four different cases were used in this study, these cases were created by varying two different constraints. The separate even flow constraint represents the an even flow of coniferous and deciduous volume from the land base and the combined represents even flow of coniferous and deciduous together over the length of the planning horizon. The ending inventory constraint was in the form of a non-declining yield of growing stock on the land base for the second half of the planning horizon.

		Ending Inventory Constraint			
		With		Without	
Flow Constraints	Separate Even Flow	Case 1	post-fire (removal)	Case 2	post-fire (removal)
			post-fire (regeneration)		post-fire (regeneration)
	Combined Even Flow	Case 3	post-fire (removal)	Case 4	post-fire (removal)
			post-fire (regeneration)		post-fire (regeneration)

Other minor modifications were made to the models additional to the variations made to the constraint sets. New area files were created as the original area file information and the spatial data sets did not perfectly match, making the exact connection between the aspatial and spatial data impossible. It was hoped that joining the spatial and aspatial data sets would have been a simple process but it was unfortunately more difficult than originally planned.

The models used in this study were similar to the model used by Armstrong and Cumming (2003), though there were some differences. The Alberta-Pacific model included two actions - clear cutting and understory protection harvesting, whereas the Sunpine model, as well as the model used by Armstrong and Cumming (2003), only included one action (clear cutting). There was a higher level of landscape attribute information tracked in both the Alberta-Pacific and Sunpine models than in the Armstrong and Cumming model. The higher level of landscape attributes allowed the model to track many different outputs throughout the model run. The base constraint sets in both the Alberta-Pacific and Sunpine model included an ending inventory constraint which was not included in the Armstrong and Cumming model. Armstrong and Cumming used a Model II (Johnson and Scheurman, 1977) formulation in their study, whereas the Alberta-Pacific and Sunpine models used a generalized Model II formulation. The difference between the model formulations was that a generalized Model II formulation allows transitions not only from harvest, but from harvest, death, or silvicultural choices (Remsoft 2003b). Also a generalized Model II formulation allows stands to transition to non-zero age classes. The Alberta-Pacific and Sunpine models also contained more yield curves than the Armstrong and Cumming (2003) model.

The transitions within both models were defined based on different characteristics. In the Alberta-Pacific model the action that occurred to the stand, and the cover type of the stand dictated the transitions. In the case of the Sunpine model the density and cover type dictated the future stand type. The transitions sections in both models were not changed from the original models as created by the companies.

Both the Alberta-Pacific and Sunpine runs were created using a generalized Model II timber harvest formulation (Remsoft, 2003b), though for the purpose of simplicity the following model explanation shows a standard model II formulation (Johnson and Scheurman, 1977). The models used closely followed that of Armstrong and Cumming (2003), which used notation similar to Dykstra (1984, p.130-137). The objective function was:

$$\max Z = \sum_{i=1}^{D} \sum_{k=1}^{H} \sum_{j=-M+1}^{k-N} \sum_{r=1}^{P} c_{ijkr} x_{ijkr} \tag{1}$$

where

Z = the value of the objective function,

D = the number of timber development type classes,

H = the number of periods in the planning horizon,

N = the minimum number of periods between harvests,

x_{ijkr} = area (ha) of forest in development type class i, born in period j, harvested in period k, managed under regime r,

M = age of oldest existing timber type, in periods,

P = the number of management regimes, and

c_{ijkr} = objective function coefficient associated with harvesting in period k, forest in development type class i, managed under regime r, that was born in period j.

All of the runs in the two models were optimized to maximize the total volume harvested (m^3) over the planning horizon. The planning horizon represented 20 periods or 200 years for the Alberta-Pacific model and 18 periods, or 180 years for the Sunpine model. In the case of the Alberta-Pacific model there were two harvest options available - either clear cutting or under story protection harvesting (P=2). In the Sunpine model there was only one action available. Therefore, P = 1 and the final summation became irrelevant for the Sunpine model.

The starting inventory was set as a constraint to ensure that the forest area was set to either a harvest or a no harvest option.

$$\begin{gathered}\sum_{k=1}^{H} x_{ijkr} + u_{ij} = A_{ij} \\ i = 1,2,\ldots,D; j = -M+1,-M+2,\ldots,0; r = 1,2\end{gathered} \tag{2}$$

where

A_{ij} = initial area (ha) of development type class *i* born in period *j*, and

u_{ij} = area (ha) of forest in development type class *i* born in period *j* that is never harvested in the planning horizon.

Area constraints were placed on the model and were used to ensure that area harvested stayed within the planning problem.

$$\sum_{i=1}^{D}\sum_{k=1}^{H-1}\sum_{r=1}^{P} x_{ikr} + u_{ik} = \sum_{i=1}^{D}\sum_{m=k+1}^{H}\sum_{r=1}^{P} x_{imr} + u_{im} \tag{3}$$

Even flow constraints were placed on the model as either separate softwood and hardwood even flow constraints or total volume even flow.

$$S_k = \sum_{i=1}^{D}\sum_{j=-M+1}^{k-N}\sum_{r=1}^{P} s_{ijkr} x_{ijkr} \qquad k = 1,2,\ldots,H-1 \tag{4}$$

$$S_k - S_{k+1} = 0 \qquad k = 1,2,\ldots,H-1 \tag{5}$$

$$D_k = \sum_{i=1}^{D} \sum_{j=-M+1}^{k-N} \sum_{r=1}^{P} h_{ijkr} x_{ijkr} \qquad k = 1,2,\ldots,H-1 \tag{6}$$

$$D_k - D_{k+1} = 0 \qquad k = 1,2,\ldots,H-1 \tag{7}$$

$$T_k = \sum_{i=1}^{D} \sum_{j=-M+1}^{k-N} \sum_{r=1}^{P} t_{ijkr} x_{ijkr} \qquad k = 1,2,\ldots,H-1 \tag{8}$$

$$T_k - T_{k+1} = 0 \qquad k = 1,2,\ldots,H-1 \tag{9}$$

where

S_k = softwood volume (m^3) harvested in period *k*,

s_{ijkr} = softwood harvest volume (m^{3}ha^{-1}) associated with development type class *i*, birth period *j*, harvest period *k*, and managed under regime *r*,

D_k = hardwood volume (m^3) harvested in period *k*,

d_{ijkr} = hardwood harvest volume (m^{3}ha^{-1}) associated with development type class *i*, birth period *j*, harvest period *k*, and managed under regime *r*,

T_k = total volume (m^3) harvested in period *k*, and

t_{ijkr} = total harvest volume (m^{3}ha^{-1}) associated with development type class *i*, birth period *j*, harvest period *k*, and managed under regime *r*.

In addition to the constraints used by Armstrong and Cumming an ending inventory constraint was placed on the model. This ending inventory constraint ensured that the growing stock in the forest did not decline over the last half of the planning horizon.

$$G_k = \sum_{i=1}^{D} \sum_{j=-M+1}^{k-N} \sum_{r=1}^{P} g_{ijr} x_{ijr} + g_{ijr} u_{ijr} \quad k = H/2, H/2+1,\ldots,H \tag{10}$$

$$(1-\alpha)G_k - G_{k+1} \le 0 \quad k = H/_2, H/_2 + 1, \ldots, H-1 \qquad (11)$$

where

G_k = total volume (m^3) on the land use in period k,

g_{ijr} = growing stock volume (m^{3}ha^{-1}) associated with development type class i, born in period j, managed under regime r,

α = maximum proportional increase in growing stock from one period to the next, and

Non-negativity constraints were also applied to all activities and areas within the model to ensure that they were positive.

$$x_{ijkr} \ge 0;\ u_{ij} \ge 0;\ S_k \ge 0;\ D_k \ge 0;\ T_k \ge 0;\ G_k \ge 0;\ \forall i,j,k \qquad (12)$$

Solving this model formulation which constrained the starting inventory (eq. 3) created the necessary shadow prices, in terms of m^{3}ha^{-1} change over the planning horizon. With these shadow prices it was possible to approximate the cost of forest fires and land base removals - the cost of the fire represented the change to the objective function value.

2.4 Methods

This study was broken down into two sections. The first section was a case study using shadow prices to approximate the costs of two real fires, using different constraint sets and regeneration scenarios. The second section was a case study using shadow prices to approximate the cost of township removals.

Fire Scenario

The cost of the House River and the Dogrib fires were initially calculated using the historical "remove and recalculate" approach. Subsequently the cost of these fires were then approximated using shadow prices. These approximations were then compared to the historical "remove and recalculate" costs of the fires to examine the accuracy of the shadow price approximations. These calculations and approximations were completed under two post-fire regeneration assumptions, and the four previously discussed constraint sets. The two regeneration assumptions align with historical and current Alberta government policy regarding the regeneration of post-fire areas. Under the historical regeneration assumption areas affected by fire are assumed not to regenerate and are permanently removed from the operable land base. Therefore the areas affected by fire do not contribute to the AAC in subsequent post-fire optimizations of the forest planning models. These areas are reincorporated into the forest planning models once they are considered sufficiently restocked, since this research is only looking at the current planning period this reincorporation is ignored. The second regeneration assumption, aligning to more current policy, has the area affected by fire immediately regenerating. Therefore the areas affected by fire contribute to the subsequent AAC in post-fire optimization of the forest planning model.

The initial step, in calculating the "remove and recalculate" cost of the fires, was the reincorporation of the fire areas into their respective land bases using the pre-fire development type classes (Figure 2.4). This provided a pre-fire land base on which the optimization could be completed. This land base data was then converted to an aspatial data set that can be used by the LP-based forest planning model. The second step in the analysis was the optimization of the LP-based forest planning models with the fire areas reincorporated, in their pre-fire states, into the land bases. The Alberta-Pacific and Sunpine LP-based forest planning models were both optimized 4 times, once for each of

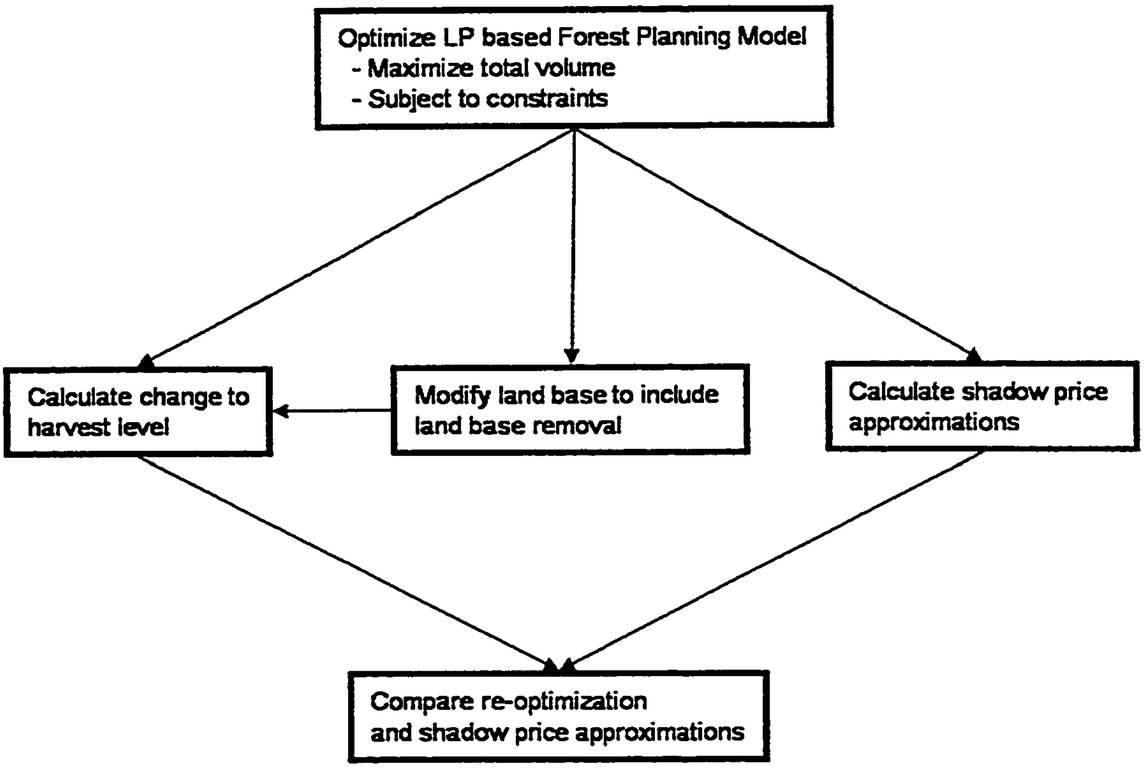

Figure 2.4. A flow chart showing the steps taken to calculate the "remove and recalculate" and shadow price approximations.

the four constraint sets (Table 2.3). After each optimization the shadow price output files were saved for later use. The third step in the analysis was the incorporation of the fire areas into their respective land bases and subsequently the land bases were compiled into aspatial data sets that could be used by the LP-based forest planning models. Initially the fires were incorporated into the land bases assuming the fire areas did not immediately regenerate, effectively this meant the fire areas were removed from the productive land base. The fourth step was the re-optimization of the LP-based forest planning models under all four constraint sets with the fire incorporated under the no regeneration assumption. These optimizations represented the post-fire AAC's, assuming no regeneration occurred. The difference between the pre-fire and post-fire optimizations, when no regeneration is assumed, is referred to as the "true" cost of the fire. This described method of removing (or modifying) the areas in the LP-based forest planning model and re-optimizing the model to measure the cost of a land base removal was referred to as the "remove and recalculate" approach. The fifth step was measuring the cost of the fires using the "remove and recalculate" approach assuming regeneration occurred post-fire. The fifth step was completed by incorporating the fire areas into the pre-fire land bases and subsequently converting the land base information into an aspatial data set for use in the LP-based forest planning models assuming the fire areas regenerated immediately. Therefore the productive land base was the same size, though the areas affected by fire were all in young development type classes. The LP-based forest planning models were then re-optimized under all 4 cases. When the fire areas were assumed to regenerate post-fire the difference between the pre-fire and post-fire optimizations was referred to as the "regeneration" cost of the fire. With this analysis completed it was possible to calculate the "true" and "regeneration" costs of the House River and Dogrib fires under all 4 constraint sets. These calculated costs were then used to test the accuracy of the shadow price approximations.

After the LP-based forest planning model runs were completed under all scenarios and cases, an attempt was made to link the shadow prices from the pre-fire runs to the spatial information. All of the spatial work within this study was done with ArcView 3.2 (ESRI, 1996). This process was expected to be straightforward as the LP-based forest planning model information was originally drawn from the spatial land base information. In practical application it proved difficult to link the shadow prices of development type classes to a spatial data set due to divergences between the LP-based forest planning model and spatial information. This will be discussed later in this thesis.

During the pre-fire optimizations the shadow price output files were saved to disk. To complete the shadow price approximations it was necessary to attach the shadow prices from the LP-based forest planning models to their respective land bases. There was 2 shadow prices needed to approximate the "regeneration" cost of a fire, whereas only one shadow price was needed to approximate the "true" cost of a fire. The shadow price required to calculate the "true" cost of a fire was the shadow price of the existing, pre-fire, development type class. The additional shadow price which was required to approximate the "regeneration" cost of a fire was the shadow price of the development type that would be assumed to regenerate post-fire. For each polygon on the land bases both of these shadow prices, the shadow price of the existing stand and the stand that would be assumed to regenerate, were attached to the spatial data sets. This process was completing by creating a link between the development type themes within the shadow price files, which corresponded to the theme information within the forest planning models, and the corresponding spatial theme information within ArcView. This process was completed once for each of the four constraint sets used, therefore there were a total of 8 shadow prices necessary to complete all of the shadow price approximations.

With shadow prices attached to the spatial data sets it was possible to calculate the shadow price approximations. The first shadow price approximations that were completed were approximations of the "true" cost of the fires. For any polygon the shadow price of the existing development type class, or pre-fire stand type, represents the cost (m^3 planning horizon^{-1}) of removing one ha of that type from the land base. Therefore the shadow price cost of removing a polygon from the land base is the shadow price of the existing development type class of the polygon multiplied by the area of the polygon. Summing the shadow price cost of removing a polygon from the land base for the entire area affected by the fire represents the "true" cost of the fire using shadow price approximations. In condensed form the shadow price approximation of the "true" cost of a fire is represented by the area weighted summation of the shadow prices of the affected area (eq. 13).

The shadow price approximations of the "regeneration" cost of the fire differ slightly from the shadow price approximations of the "true" cost of the fires. Two transformations are assumed to occur when a fire occurs on the land base and the area is assumed to regenerate post-fire. First the fire is assumed to destroy the kill the existing stand, therefore there is a cost of the fire, which can be represented by the shadow price of the stand that was killed. The second transformation is the addition of a new, young, stand to the land bases, which effectively adds the shadow price of the new development type class to the cost of removing the existing development type class. The shadow price approximation of the "regeneration" cost of burning one ha of the land base is the shadow price of the existing development type class subtracted by the shadow price of the development type class that is assumed to regenerate post-fire. The shadow price approximation of the "regeneration" cost of burning a polygon on the land base is the shadow price approximation of the "regeneration" cost of burning one ha multiplied by the area of the polygon. By summing the shadow price approximation of the "regeneration" cost of burning all of the affected polygons on the land base the shadow price approximation of the "regeneration" cost of the fire is produced (eq 14.)

These shadow price approximations were completed for both the House River fire and the Dogrib fire, under all 4 of the cases used in the study. The shadow price calculations can be summarized by equation 13 when the area is removed from the land base and equation 14 when the area is assumed to regenerate.

$$\sum_{i=1}^{H} SP_i^{\alpha} \bullet x_i \tag{13}$$

$$\sum_{i=1}^{H} ((SP_i^{n} - SP_i^{r}) \bullet x_i) \tag{14}$$

where:

H = Number of polygons in area of interest
SP_i^n = Shadow price of polygon *i*, when the land base is removed from production post-fire
SP_i^r = Shadow price of polygon *i*, when the land base is regenerated post-fire
x_i = Area in polygon *i*

Comparisons between the "true" and "regeneration" cost of the fires and shadow price approximations of these costs allowed the accuracy of the shadow price approximations to be tested. The "true" cost or "regeneration" costs of the fires were divided by the equivalent shadow price approximations providing a ratio of the difference between the measures. This ratio was used to examine the accuracy of the shadow price approximations and allowed a simple comparison to previous studies. The numerical differences between the "true" and "regeneration" costs and shadow price approximations of these costs were also calculated and compared.

Township Scenario

The township removal scenario was completed on a reduced scale due to the initial results from the fire scenarios. Initial results showed that the regeneration approximations were considered inaccurate: therefore, no regeneration approximations were completed. All of the cases showed similar results, so only one constraint set was selected. Case 1, separate even flow of softwood and hardwood with an ending inventory constraint, was run on the Alberta-Pacific model. Case 1 represented the base formulation of the model as it was obtained from Alberta-Pacific.

The procedure used to complete the township scenario was very similar to the procedure used in the fire scenarios. A minor change was made to the LP-based forest planning model. This change was the inclusion of the township a polygon was within as an additional theme in the LP-based forest planning model. With this information in the starting inventory, a base, or pre land base removal, optimization was completed. The House River fire area was included in its pre-fire state. This optimization produced the same solution as the case 1 pre-fire optimization from the fire scenarios, but included the township information in the shadow price output files. The shadow price output file was saved to disk for use in the shadow price approximations. Following the base, or pre land base removal, optimization the "true" cost of removing each township from the land base was calculated using the "remove and recalculate" approach. The procedure used to calculate the "true" cost was the same as in the no regeneration fire scenario. With the "true" costs of the township removals calculated the shadow prices were then attached to the spatial land base data. The shadow price approximations were then calculated for each of the townships in the land base using equation 13, which represents the area-weighted shadow price summation used in the no regeneration fire scenario. The resulting shadow price approximations and optimization calculations were then analyzed in the same manner as the fire scenarios. Also the amount of area within each township, and the amount of the township burnt by the House River fire was identified.

2.5 Results and Discussion

It was initially thought that the process of joining the aspatial forest planning model data to the spatial map data would be simple. Disappointingly, it was discovered to be a more difficult task than expected. During the process of creating a forest planning model, forest companies begin with a spatial map data set containing polygons classified into themes based on their attributes. The spatial map data set was then compiled to an aspatial file that shows the aggregated amount of area in each development type class on the land base. At this point there was a definitive connection between the two data sets. Therefore, adding the shadow prices to the spatial data set at this point should be a simple process.

However, both of these data sources are dynamic, and constantly change as more data is available and knowledge changes. Typically spatial data sets are constantly updated with new information but LP-based forest planning models, since only needed during long term planning, are not updated with all of the newly available information. Also, the aggregated data in LP-based forest planning models is often modified to remove unnecessary or redundant information to improve run times or simplify the model. Since the spatial and aspatial data sets are changed at different rates, the connection between them often disappears, making the exact connection between them difficult.

When trying to complete this join for the Alberta-Pacific land base it was discovered that the total area within the different spatial and aspatial themes was very close but not exact. When this small error in the individual themes was combined, the overall error became substantial enough to make the calculated values inaccurate for use in this study. It was decided it would be very difficult to join these two data sets as obtained from the two companies without error. Instead area files were recreated and incorporated into the models. Therefore all of the resulting calculations differed to a minor degree from the original models obtained from the companies, but the join between the spatial and aspatial data sets matched exactly for the transfer of data.

Fire Scenarios

The different scenarios and cases resulted in different optimized harvest levels during the pre-fire optimizations (Table 2.4). In the post-fire no regeneration scenario the optimized harvest levels differed between in all cases, and on both the land bases but all of the optimized harvest levels were lower than the pre-fire optimizations. The Alberta-Pacific and Sunpine optimizations both showed decreases of approximately 8% and 2% respectively in the optimized harvest levels post-fire. On the Alberta-Pacific land base the "true" cost of the House River fire varied from 4.7 million to 5.2 million m^3 over the planning horizon. On the Sunpine land base the "true" cost of the Dogrib fires ranged from 3.4 million to 3.7 million m^3 over the planning horizon. This positive "true" cost of the fires, or decline in harvest was to be expected, since there was less standing volume and incremental growth, which cause a lower optimized harvest level under an even flow constraint, which was imposed in all cases. The post-fire regeneration scenario on the Alberta-Pacific land base showed different optimized harvest levels for all of the cases examined. The "regeneration" cost of the House River fire ranged from -2,000 to 500,000 depending on the case. The "regeneration" cost of the Dogrib fire range from 450,000 to 620,000 depending on the case. The ratios of "regeneration" cost to shadow price approximation for the House River fire varied from a 0.01% increase to a 0.79% decrease from the pre-fire optimizations. All of the cases from the Sunpine post-fire regeneration scenario showed a decrease of approximately 0.25% in the optimized harvest level.

Table 2.4. All of the model runs produced varying harvest levels based on the constraint, as well as changes when the fires areas were placed on the land base.

			Optimized harvest level (m^3)	Change in harvest from base run (m^3)	% change	AAC (m^3/yr)	AAC change (m3/yr)
Alberta-Pacific	*Case 1*	pre-fire	57,995,647			289,978	
		post-fire (removal)	53,299,109	4,696,538	8.10%	266,496	23,483
		post-fire (regeneration)	57,998,579	-2,932	-0.01%	289,993	-15
	Case 2	pre-fire	63,002,557			315,013	
		post-fire (removal)	57,815,446	5,187,110	8.23%	289,077	25,936
		post-fire (regeneration)	62,840,925	161,631	0.26%	314,205	808
	Case 3	pre-fire	58,355,224			291,776	
		post-fire (removal)	53,633,551	4,721,673	8.09%	268,168	23,608
		post-fire (regeneration)	58,267,334	87,891	0.15%	291,337	439
	Case 4	pre-fire	64,068,336			320,342	
		post-fire (removal)	58,885,454	5,182,882	8.09%	294,427	25,914
		post-fire (regeneration)	63,564,681	503,656	0.79%	317,823	2,518
Sunpine	*Case 1*	pre-fire	195,331,883			1,085,177	
		post-fire (removal)	191,629,812	3,702,071	1.90%	1,064,610	20567
		post-fire (regeneration)	194,880,827	451,056	0.23%	1,082,671	2506
	Case 2	pre-fire	207,278,135			1,151,545	
		post-fire (removal)	203,921,627	3,356,508	1.62%	1,132,898	18647
		post-fire (regeneration)	206,717,932	560,203	0.27%	1,148,433	3112
	Case 3	pre-fire	196,072,115			1,089,290	
		post-fire (removal)	192,364,502	3,707,613	1.89%	1,068,692	20598
		post-fire (regeneration)	195,607,583	464,532	0.24%	1,086,709	2581
	Case 4	pre-fire	208,603,884			1,158,910	
		post-fire (removal)	205,234,388	3,369,496	1.62%	1,140,191	18719
		post-fire (regeneration)	207,983,059	620,825	0.30%	1,155,461	3449

The changes to harvest levels in both scenarios and all cases were at least in part a function of the even flow constraint on the models. When area was removed from the land bases there was a decrease in the optimized harvest level; in both cases it was approximately equal to the proportion of the land base removed. When the fire area was reincorporated into the land base as regenerating development type classes, there was an increase in harvest from the land base removal optimizations as the incremental growth from the land base increased. Adding this young fast growing timber to the land bases could be causing an Allowable Cut Effect (ACE) in some of the cases. This is due to the addition of fast growing timber to the mature and over-mature timber on the land bases, particularly on the Alberta-Pacific land base. Adding fast growing timber to a mature and over-mature forest causes an ACE effect, which allows for an increased rate of harvest of the mature and over-mature forest (Schweitzer *et al.*, 1972). This ACE was especially present in Case 1 of the Alberta-Pacific post-fire regeneration scenario, as there is a slight increase in the optimized harvest level from the pre-fire to the post-fire regeneration scenario.

The distribution of shadow prices differed between the two land bases, scenarios and cases examined. Figure 2.5 shows boxplots of the distribution of the starting inventory shadow prices. The middle line of the box represents the median of the distribution; the upper and lower edges of the boxes represent the 75 and 25 percentiles, respectively. The whiskers of the boxplot show 1.5 times the interquartile distribution. The distribution of shadow prices on the Alberta-Pacific and Sunpine land bases differ. The boxplot of the shadow prices from the Sunpine model show that by removing the ending inventory constraint from the model the distributions of shadow prices are lower (Figure 2.5). It is believed that this is due to the LP-based forest planning model not needing to maintain the growing stock on the land base into perpetuity, which decreases the value of regenerating the harvested land base and therefore decreases the harvestable volume from development types. This was the only apparent difference between shadow

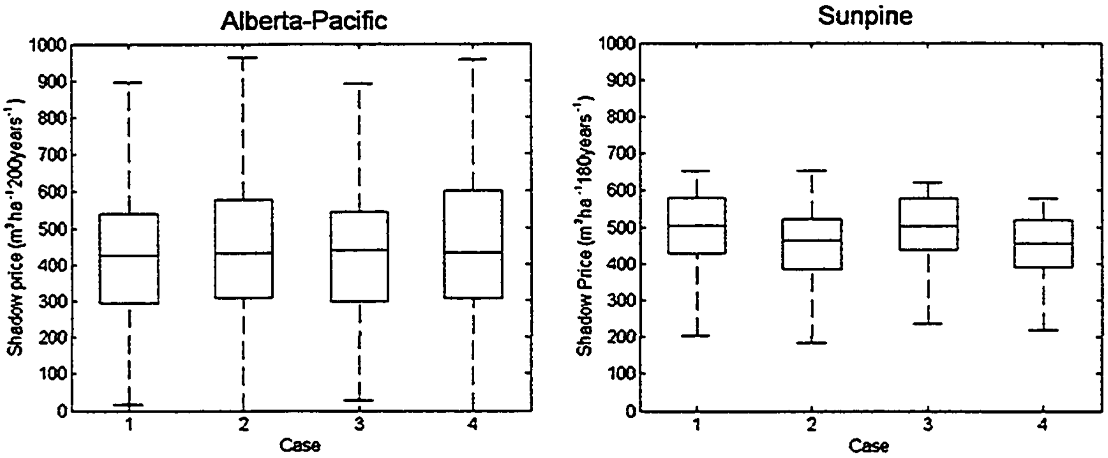

Figure 2.5. The distributions of shadow prices shown as box plots for both land bases.

prices distribution from the different cases examined. The spatial distributions of these shadow prices on the land bases can be seen in figures 2.6 and 2.7. These figures represent a timber value at risk map. The color scale represents a gradient of the cost of removing one ha of that development type class. Therefore the darker areas represent areas where the area contributes more towards the achievable harvest from the land base. Individual development types shadow prices show a wide variety of trends in shadow prices value through different starting ages (Figure 2.8). Where the boxplot represent the aggregation of all shadow prices from the land base, figure 2.8 shows the change in an individual starting inventory development type as age changes. Some of these starting inventory development type shadow price curves decreased, others increased, and some showed normal curves, increasing then decreasing. Decreasing shadow prices curves show that young timber of the development type provide a larger contribution to the objective function value than older timber of the same development type. The opposite is true of the increasing shadow price curves. Generally shadow price curves over differing starting ages did not show any sudden changes in values.

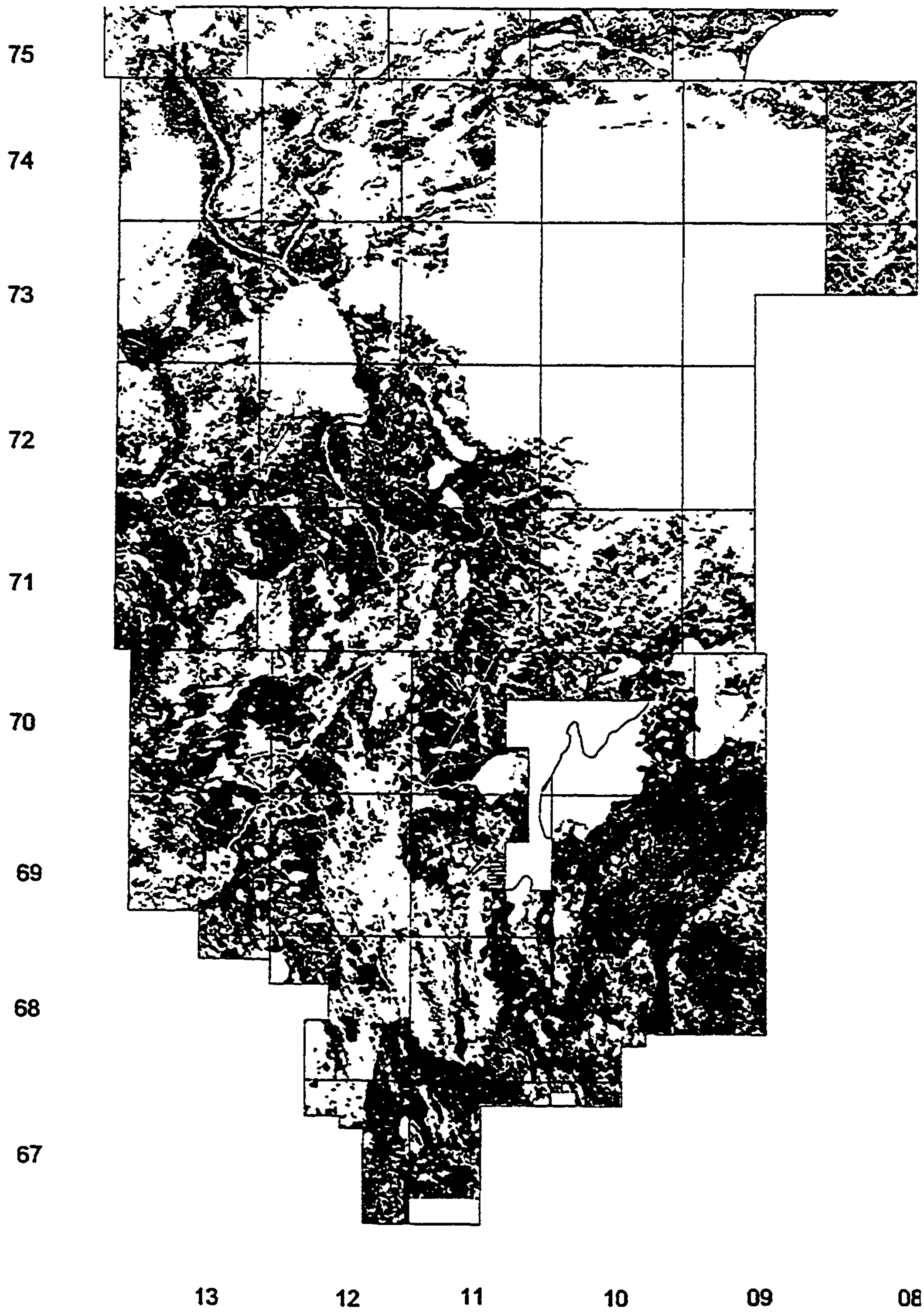

Figure 2.7. A shadow price map showing the polygon contribution within FMU L1: where the shadow prices of the starting inventory are represented by a graduated color scale where white = 0 m^3ha^{-1} and black = 896 m^3ha^{-1} over the planning horizon.

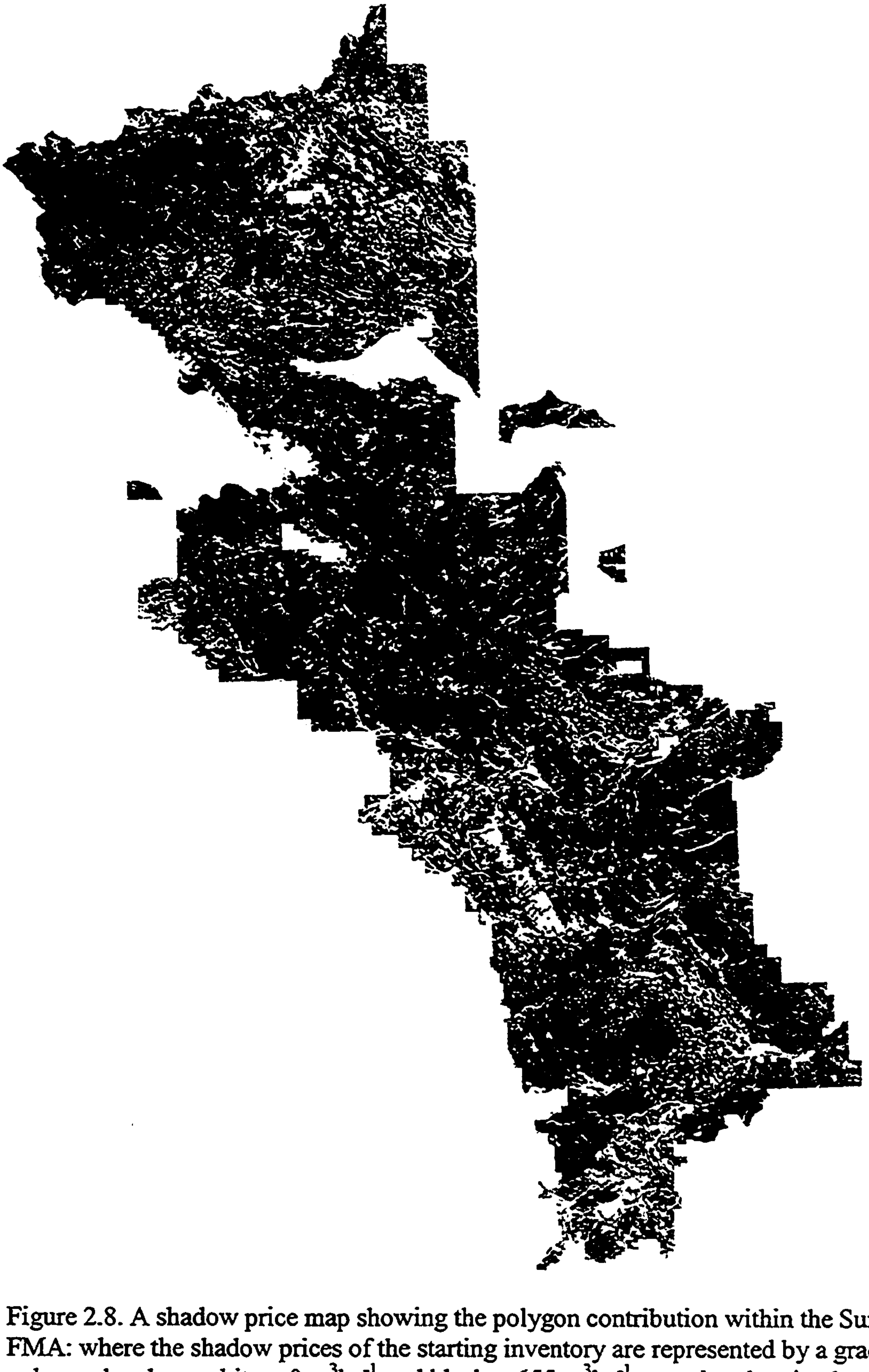

Figure 2.8. A shadow price map showing the polygon contribution within the Sunpine FMA: where the shadow prices of the starting inventory are represented by a graduated color scale where white = 0 m^3ha^{-1} and black = 655 m^3ha^{-1} over the planning horizon.

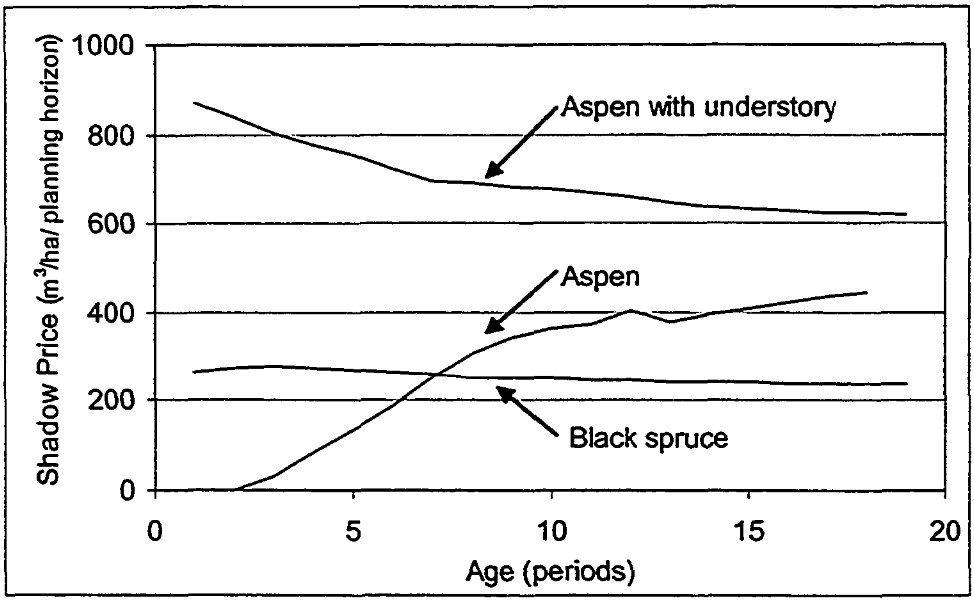

Figure 2.6. The shadow prices of the starting inventory constraints varied greatly. Some forest types increased such as the aspen type shown, some decrease such as the aspen with understory, while some stayed constant over time such as the black spruce type shown.

When the "true" costs of the fires were compared to the shadow price approximation, the results were very similar for all cases examined (Table 2.5). For all of the Alberta-Pacific cases the ratio of the "true" cost of the House River fire to the shadow price approximation was approximately 0.999. This meant the shadow prices produced very accurate results for approximating the cost of the House River fire under all constraint sets examined. For all of the Sunpine cases the ratio of the "true" cost of the fire to the shadow price approximation was approximately 1.03. Therefore, for both fires examined the shadow price approximations proved to be very effective at approximating the cost of the fires when the land base was removed from production. Paredes and Brodie (1988) showed that the sum of the area weighted shadow prices of the entire land base is equal to the objective function value and Armstrong and Cumming (2003) stated that removing the same proportion of all development types would allow shadow prices to exactly measure the cost of land base removals. The results from this section concur with the results from the study by Armstrong and Cumming (2003) which found that shadow prices accurately estimated the "true" cost of fires.

Table 2.5. The optimization differences between the fire scenarios and the shadow price estimations differed to varying degrees in all cases.

			Optimized difference (m^3)	Shadow price difference (m^3)	Ratio	Numerical difference between estimations (m^3)
Alberta-Pacific	Case 1	post-fire (removal)	-4,696,538	-4,693,674	0.9994	-2,864
		post-fire (regeneration)	2,932	89,271	30.4472	-86,339
	Case 2	post-fire (removal)	-5,187,110	-5,183,771	0.9994	-3,339
		post-fire (regeneration)	-161,631	50,755	-0.3140	-212,386
	Case 3	post-fire (removal)	-4,721,673	-4,718,612	0.9994	-3,061
		post-fire (regeneration)	-87,891	-37,042	0.4215	-50,848
	Case4	post-fire (removal)	-5,182,882	-5,177,077	0.9989	-5,805
		post-fire (regeneration)	-503,656	-334,405	0.6640	-169,250
Sunpine	Case 1	post-fire (removal)	-3,702,071	-3,819,638	1.0318	117,567
		post-fire (regeneration)	-451,056	-560,821	1.2434	109,765
	Case 2	post-fire (removal)	-3,356,508	-3,463,928	1.0320	107,420
		post-fire (regeneration)	-560,203	-656,431	1.1718	96,228
	Case 3	post-fire (removal)	-3,707,613	-3,825,666	1.0318	118,053
		post-fire (regeneration)	-464,532	-576,766	1.2416	112,234
	Case4	post-fire (removal)	-3,369,496	-3,476,381	1.0317	106,885
		post-fire (regeneration)	-620,825	-722,262	1.1634	101,437

The regeneration scenario produced different results than the no regeneration scenario. The ratios of "regeneration" cost of the House River fire to the shadow price approximations showed large variations between the cases (Table 2.5). The ratios ranged from -0.31 to 30.45, while the other two ratios were around 0.5. The ratio of 30.45 in case 1 was a large proportional difference though the absolute difference is approximately equal to that of the other "regeneration" costs to shadow price approximations. The reason the ratio in case 1 was so large is that the denominator of the ratio, the regeneration cost of the fire, was a small number. This caused the ratio to be large, even though the absolute difference was in the same range as the other cases. For the Sunpine regeneration scenario the ratios of "regeneration" cost of the Dogrib fire to the shadow price approximation of the fire were similar, ranging from 1.16 to 1.24. This was believed to be unacceptable, though the absolute differences were consistent between all of the approximations. Overall, in contradiction to the results from Armstrong and Cumming (2003), the shadow price approximations were inaccurate for approximating the costs of forest fires when regeneration was assumed. It is believed this was due to the changes to the starting inventory being outside of the bounds within which the shadow prices were accurate. Many of the young development type classes that regenerated post-fire did not occur within the starting inventory. In the regeneration scenarios large amounts of area were placed within these new development type classes, and it is believed that these changes to the starting inventory were so large that the bounds in which the shadow prices were accurate within were violated. This would change the optimal solution, creating a different set of shadow prices. This effect was not seen when removing area from the land base as the development type classes removed already existed on the land base prior to the fire, therefore the resulting shadow price values were believed to be more robust to change. Despite the initial results and optimism from Armstrong and Cumming (2003), shadow price approximations were not found to be sufficiently accurate when regeneration was assumed post-fire. However, when regeneration was assumed there was still the possibility to use shadow price approximations for rough estimations of the cost of fires.

Township Scenario

The results from the township removal scenario were very consistent. Each township within FMU L1 contributed a different amount to the optimized harvest level (Table 2.6). The differing contributions to the harvest were caused by a number of factors: the amount of area in the township within the FMU, and the amount of each development type class within the township. It can be seen in figure 2.7, which represents the shadow price value of the development type class in the polygons within FMU L1, that there was a large area with zero shadow prices associated in the northeastern corner of the FMU. This area represents a subsection of FMU L1 that does not contribute to the objective function. The ratios of the "true" cost of removing the township to the shadow price approximation were approximately 1.00 for all of the townships. The presence of the House River fire within the township did not affect the accuracy, showing that the method was accurate in all areas of FMU L1, not only the fire analysis area. Overall this method showed high levels of accuracy when the townships were removed from the productive land base. This contradicts other research that used shadow prices to approximate the cost of land base removals (R. Stronach, and K. Peck, Alberta Sustainable Resource Development. pers. comm.). The difference between the two models was not explainable as the unpublished work was not available for comparison.

Table 2.6. The townships within FMU L1, showing the harvest levels, shadow price approximations, as well as the ratio of optimized change to the shadow price approximation. There is also information about the amount of area in the township within the FMU and the proportion of the township burnt by the House River fire.

Township (township-range-meridian)	Optimized harvest level (m^3)	Change in harvest from base run (m^3)	Shadow price difference (m^3)	Ratio	Numerical difference between estimations (m^3)	Area within township in FMU	Area in township in FMU burnt by House River fire	Percent of township in FMU burnt by House River Fire
74-10-W4	57,557,104	149,589	149,569	1.0001	21	9,446	3,333	35%
74-11-W4	56,754,745	951,949	950,848	1.0012	1,101	9,448	3,319	35%
70-10-W4	56,039,457	1,667,237	1,666,333	1.0005	904	7,597	0	0%
73-11-W4	57,360,853	345,841	345,698	1.0004	143	9,480	292	3%
75-10-W4	57,010,043	696,650	696,624	1.0000	26	4,769	4,297	90%
75-13-W4	57,202,578	504,115	504,091	1.0000	24	4,775	0	0%
73-08-W4	56,948,848	757,846	757,771	1.0001	75	4,725	0	0%
71-11-W4	54,978,384	2,728,309	2,727,402	1.0003	907	9,554	0	0%
74-12-W4	56,700,946	1,005,748	1,005,413	1.0003	335	9,447	7,098	75%
72-11-W4	55,741,057	1,965,637	1,964,573	1.0005	1,063	9,500	0	0%
73-13-W4	56,372,242	1,334,452	1,333,937	1.0004	515	9,479	119	1%
71-10-W4	56,263,895	1,442,798	1,441,787	1.0007	1,011	9,554	0	0%
69-10-W4	54,242,786	3,463,908	3,462,916	1.0003	992	9,479	0	0%
71-09-W4	56,911,798	794,895	794,773	1.0002	122	4,776	35	1%
74-09-W4	57,370,643	336,051	336,051	1.0000	0	9,452	2,995	32%
71-13-W4	54,918,372	2,788,322	2,788,135	1.0001	187	9,562	0	0%
70-11-W4	55,453,632	2,253,062	2,253,025	1.0000	37	7,902	0	0%
71-12-W4	55,435,377	2,271,316	2,271,016	1.0001	300	9,556	0	0%
75-08-W4	57,699,150	7,544	7,544	1.0000	0	42	42	100%
70-09-W4	56,887,692	819,002	818,692	1.0004	310	4,735	0	0%
72-10-W4	57,546,141	160,553	160,552	1.0000	0	9,501	0	0%
69-09-W4	56,033,493	1,673,201	1,672,874	1.0002	327	4,742	0	0%
68-13-W4	57,548,742	157,952	157,951	1.0000	0	786	0	0%
70-12-W4	55,729,431	1,977,262	1,977,243	1.0000	19	9,518	0	0%
72-12-W4	55,561,693	2,145,001	2,144,883	1.0001	118	9,499	0	0%
69-11-W4	55,630,163	2,076,530	2,076,205	1.0002	326	7,901	0	0%
68-09-W4	56,490,013	1,216,681	1,215,540	1.0009	1,141	3,166	0	0%
69-13-W4	55,693,339	2,013,355	2,012,958	1.0002	397	8,661	0	0%
75-09-W4	57,325,276	381,417	381,414	1.0000	3	2,975	2,544	86%
69-12-W4	55,981,489	1,725,205	1,725,163	1.0000	41	9,475	0	0%
68-10-W4	55,059,717	2,646,977	2,646,523	1.0002	454	8,052	0	0%
70-13-W4	55,346,955	2,359,739	2,358,856	1.0004	883	9,481	0	0%
67-11-W4	56,021,413	1,685,281	1,685,202	1.0000	78	5,556	0	0%
72-13-W4	55,902,952	1,803,742	1,803,335	1.0002	406	9,500	0	0%
67-12-W4	56,464,870	1,241,824	1,238,667	1.0025	3,157	4,294	0	0%
68-11-W4	55,254,132	2,452,562	2,451,005	1.0006	1,557	9,508	0	0%
73-12-W4	56,545,384	1,161,310	1,161,164	1.0001	146	9,478	3,846	41%
74-08-W4	56,463,448	1,243,246	1,242,182	1.0009	1,064	9,441	2,266	24%
74-13-W4	56,571,168	1,135,526	1,135,414	1.0001	112	9,448	0	0%
68-12-W4	56,226,693	1,480,001	1,479,731	1.0002	270	7,517	0	0%
75-12-W4	57,522,995	183,699	183,698	1.0000	1	4,774	2,686	56%
67-10-W4	57,527,460	179,234	179,224	1.0001	10	788	0	0%
75-11-W4	57,365,968	340,725	340,712	1.0000	13	4,773	4,234	89%

The "remove and recalculate", or traditional, approach to calculating the cost of land base removals is very time consuming. Using a dual Pentium IV 2 GHz system with 2 gigabytes of RAM it took approximately 7 minutes to create and solve the constrained optimization problem. This excludes the most time consuming process which is removing the fire area from the LP-based forest planning model. This process took from 20 minutes up to an hour depending on the complexity of the fire. When using shadow prices it is possible to draw any fire polygon on the same computer system, and calculate the losses from the fire in less than 1 minute. Possibly the largest advantage to this method is that land base removal costs can be approximated by anyone with the ability to draw predicted or actual fire shapes on a PC with GIS software installed. When using a "remove and recalculate" approach someone trained in both GIS and timber supply is needed to accurately estimate the cost of fires. Therefore fire costs could be estimated simply on more fires, to minimize the losses to harvest from fires by comparing different possible fire shapes, and deploying resources to minimize losses. This method could also be used in the same manner to approximate the losses to land base removals from other causes such as well sites or pipelines.

This study was limited to two land bases within Alberta, both of which used constrained optimization problems to calculate the optimal harvest level given certain constraint sets. The results of this study, when combined with those of Armstrong and Cumming (2003), suggest that using shadow prices to approximate the cost of fires and land base removals could be very useful, with certain limitations. The limitations to this method are first that shadow prices are only created through the constrained optimization problems, therefore other if another type of forest planning model is used this method is not possible. Secondly are only seen to be accurate given that the affected areas are removed from the productive land base post disturbance.

Future research within the area could include the use of goal programming and shadow prices to estimate the cost of multiple values simultaneously. Goal programming is a method of optimizing a problem for multiple objectives (Davis, et al. 2001). These objectives could include timber production, wildlife habitat or any other measurable value. Goal programming problems set a given level of each objective as a constraint on the problem. There are penalties for deviating from the set levels of the objective. Solving the goal programming problem minimizes the deviation from the set levels based on the penalty functions placed on the objectives. In theory shadow prices could be used to measure the cost of multiple objectives. Additionally there is interest in the use of this method under different modeling types such as simulation modeling, although this would mean finding a method of approximating shadow prices or a similarly representative value from this type of modeling.

2.6 Conclusion

This study showed mixed results for the applicability of using shadow prices to approximate the cost of forest fires and land base removals. Shadow prices appear to be effective under different model formulations on different land bases, as long as the areas affected are assumed to be removed from the land base in subsequent calculations. When the land base is regenerated post-fire the results showed that shadow prices produce poor approximations for the cost of forest fires. The combination of the results of this study with those by Armstrong and Cumming (2003) suggest that this method could be a useful tool in approximating the cost of land base removals and forest fires rapidly when the land base is removed from the calculations.

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Chapter 3.

Effects of fire salvage policy on long term timber supply in the boreal forest.

3.1 Introduction

Alberta's boreal forest plays a large role in the economy and ecological diversity of the province (Alberta Environmental Protection, 1998). The boreal forest provides benefits to society from many economic sources including timber, oil and gas reserves, and tourism. It also provides habitat for many endangered species including woodland caribou and whooping cranes. The structure of the boreal forest of today is largely a result of forest fires (Johnson, 1992), and fire will likely continue to shape the structure of the boreal forest in the future. There is an increasing level of human activity in the boreal forest as technological change allows the utilization of resources that were historically not accessible. It has been argued that the current level of human activity in the boreal forest, when combined with forest fires, is unsustainable (MacKendrick, *et al.*, 2001; Schneider,*et al.*, 2003).

Forest management planning is a complex process completed on different spatial and temporal scales. The most comprehensive higher level plans that must be completed by forestry companies in Alberta, every 5-10 years, are detailed forest management plans (DFMPs) (Alberta Sustainable Resource Development, 1998a). DFMPs outline the long term objective for managing the forest area in which a company has rights to harvest. They also must include an analysis of the timber supply and the level of harvest that will be undertaken annually or the Annual Allowable Cut (AAC). In Alberta an AAC must be based on the sustained yield principle and be supported by a forest planning model (Alberta, Province of, 2000). Sustained yield represents the maximum amount of timber that can be harvested annually from a defined area into perpetuity without change to the harvest level (Davis *et al.* 2001). Forest planning model are tools used schedule harvest on a land base to maximize/minimize an objective, commonly harvest level, over a specified period of time subject to user defined constraints. They require an accurate inventory of the existing forest, estimates of forest growth rates, and assumptions such as the transitions that will occur after harvest or stand death. There are different types of forest planning models; one type commonly used is linear programming (LP)-based forest planning models. LP-based forest planning models use linear programming solvers to find an optimal solution to the forest planning problem. Other types of forest planning models such as simulation-based forest planning models do not necessarily find the optimal solution to the forest planning problem. LP-based forest planning models can also be set up solve for other objective functions such as: maximizing net present value, minimizing the average harvest cost, or maximizing the habitat available. This spatially allocated harvest level is what is used to determine the AAC.

There are circumstances, other than inclusion in DFMPs, in which forest planning models must be created or updated. One of these circumstances is a major change to the land base in which a company has rights to harvest timber from. This major change to the land base may be caused by many things including forest fires or land base removals. The Alberta government has defined a major change as anything that causes a decrease of greater than 2.5% to either the defined area in which a company has rights to harvest from or AAC (Alberta Sustainable Resource Development, 2002). In this study the 2.5% recalculation trigger is ignored as re-planning occurs every five years regardless of changes to the land base or AAC.

In this study the LP-based forest planning model used was created in Woodstock, which is a program specifically designed for the creation of forest planning models (Remsoft, 2003a). Woodstock requires the user of the model to define numerous inputs. Some of these inputs include: the lifespan of stands, the yield curves associated with stands, the transitions of stands post harvest or death, and the objective function and constraints. Based on these inputs Woodstock creates a matrix that can be solved by a linear programming solver. In this study Mosek was used to solve the matricies created by Woodstock (Mosek ApS, 2002). The solver calculates the optimal activity levels to undertake to maximizes the objective function value subject to the constraints defined by the user. The results from the solver are then read by Woodstock, which generates user defined reports.

Many LP-based forest planning models are aspatial and the solutions list the activities and levels at which these activities should occur on each forest type. Spatially allocating the LP-based forest planning model solution has historically been done manually using maps and coloured pencils. When spatially allocating the LP-based forest planning model solution additional constraints are incorporated. These additional constraints include maximum and minimum block sizes, and green-up delays. Both of which decrease the maximum harvest possible (Nelson and Finn, 1991; O'Hara *et al.* 1989). This means the entire volume scheduled by the LP-based forest planning model may not be able to be feasible scheduled onto the land base without violating these additional constraints. This is expected as adding binding constraints to a problem will change the optimal solution.

Numerous computational methods can also be used to spatially allocate harvests. Each of these computational methods has its own strengths and weaknesses (Boston and Bettinger, 1999). The optimal solution to a spatial allocation problem can be found using integer programming. This method may provide an optimal solution, but creating and solving integer programming models can be time consuming and difficult (Daust and Nelson, 1993), if at all possible on an operational level. Different heuristic methods can also be used to solve spatial allocation problems some of these heuristic methods include Monte Carlo simulations, simulated annealing, and tabu searches (Clements *et al.*, 1990; Lockwood and Moore, 1993; Bettinger *et al.*, 1997). These methods provide rapid solutions. The disadvantage of these methods is that the solutions are not necessarily optimal (Daust and Nelson, 1993; O'Hara *et al.*, 1989). Monte Carlo simulations randomly assign actions on the land base and evaluate the objective function value of the assignment; this process is repeated many times and the assignment that obtains the highest objective function value is accepted as the final solution (Davis et al., 2001). One commercial available program which uses Monte Carlo simulation to solve spatial allocation problems is Stanley (Remsoft, 1999). Stanley uses the standard outputs from Woodstock to spatially allocate the aspatially scheduled harvest onto the landscape subject to constraints on volume flow, block size, and green-up delay. Monte Carlo simulations solutions are often at least 3% below the optimal integer programming solution (Daust and Nelson, 1993; Nelson and Brodie, 1990). Monte Carlo simulations are often used as they are simple to create and solve, even though the solutions are normally lower than the integer programming optimum solution. They can also be run for longer periods of time and decrease the chance of a suboptimal solution.

Sequential re-planning scenarios allow long term trends to be analyzed in the current period. When an AAC is determined it is meant to be implemented onto the defined land base from the start date of the plan, year 0, until the end of the planning horizon, which is 200 years in the future in this study. However as the AAC must be re-determined every 5 to 10 years, in this study every 5 years, the year 0 AAC is not actually implemented for the entire 200 years, but rather only 5 years. It is possible to approximate what the new AAC will be at year 5 by aging the forest by 5 years and resetting the age of any stands that were planned for harvest, or were assumed to die to be 1 period old and re-determining the AAC. This newly determined AAC is then meant to be implemented from year 5 to 205, though at year 10 it must again be re-determined. This re-determination of new future AAC's in the current time period is referred to as sequential re-planning. In this study the AAC is determined for the next 100 years, using 5 year time steps. It is expected that each AAC determined will differ from the previous given the model formulation used. It is also possible to include other events onto the land base between the AAC re-determination to approximate the effect of these other events on the harvest level. The approximation of the effect of these included events is done by comparing simulations with the events included to simulations without the events included. The difference between the simulations would then be the affect of the event of the harvest level. In this study simulated forest fires were incorporated on the land base prior to AAC re-determination to approximate their effect on the future harvest level. Armstrong (2004) used sequential replanning to examine the probability of sustainability of harvest level when fires are incorporated into an aspatial forest planning model.

Fires are stochastic events that are impossible to predict with exact certainty. There are models that are able to predict fire spread depending on current weather conditions, fuel characteristics, and topography. One such model is Prometheus which estimates fire sizes and shapes (Anonymous, 2004). Models such as Prometheus are not designed to predict future fire patterns on the landscape. Some fire models are meant to predict possible fire patterns on the landscape (Feng, 2004; Hargrove *et al.*, 2000). These models are broken down into three separate streams of research by Mladenoff and Baker [ed.] (1999). The difference in these model types is the latter's ability to create random fire starts and weather conditions whereas Prometheus is meant to have these factors as inputs. Feng's (2004) fire model uses the cellular automata theory with a hexagonal grid to create fires on a landscape. Cellular automata uses a grid system and discrete time steps to approximate spread in which a cell's state is determined based on the cell's previous state, and its neighbors previous state. Feng's (2004) fire model requires only species and land use information to be known to create fires on the landscape. The model does not predict small fires (<12 ha) accurately. This is due to the use of 3 ha hexagons in the model. The model is able to predict large fire sizes, shapes and islands effectively when compared to other models and historical fires. This model has promise for creating future fire patterns as it quickly and efficiently is able to predict large fires, which have the largest impact on the landscape. The advantage of the hexagonal grid the model uses is that all 6 neighboring hexagons are exactly equidistant away from the center of any hexagon and the perimeter area shared by each neighboring hexagon is equal.

Tenure holders in Alberta must salvage operable damaged timber from within their defined operating area or possibly be penalized (Alberta Sustainable Resource

Development 2000). Burnt timber is included in this damaged timber category. Burnt timber is only harvestable for a short period of time post-fire (commonly 2 years) as it rapidly degrades post-fire (Watson and Potter, 2004). Tenure holders have a number of options available for dealing with post-fire areas based on the government's fire salvage policy (Alberta Sustainable Resource Development, 2002). In the historical fire salvage policy post-fire areas are removed from the operable land base during subsequent AAC determinations. The burnt areas are then normally reincorporated into AAC determinations once they are considered to be sufficiently restocked. More recent policy allows companies to regenerate post-fire areas and retain these areas in subsequent AAC determinations as regenerating timber. In both of these options, the salvaged volume from the area does not count towards a company's AAC. Additional to salvage volume not counting against a company's AAC, there are also lower, damaged, timber dues charged to companies for harvesting the timber (Alberta Sustainable Resource Development, 2001). A plausible change to fire salvage policy is salvaged volume counting against a company's AAC. This would likely cause a larger portion of salvageable timber to be left on the land base in years with high levels of fire. It is expected that the manner in which post-fire areas are dealt with would change the long term harvest levels available from a defined area.

The objective of this study is to examine how different fire salvage policies effect long term harvest levels. This will be done using sequential re-planning simulations which incorporate simulated fires into an operationally realistic forest planning model. This paper will start by describing the study area and then the modeling procedures used for the aspatial forest planning model, spatial harvest allocation and fire modeling. The results will then be shown and discussed in detail followed by concluding comments.

3.2 Study Area

The study areas for this research are in northeastern Alberta, Canada (Figure 3.1). The larger of the two study areas is an extension of the smaller, primary, study area. The primary study area, used for the LP-based forest planning model and spatial harvest allocation, is forest management unit (FMU) L1 within Alberta-Pacific Forest Industries Inc.'s Forest Management Agreement (FMA) area. FMU L1 is 334,000 ha in size, of which only 43% are of harvestable forest types. The main tree species in this area are aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), and black spruce (*Picea mariana* (Mill.) B.S.P.). The spatial information available for the primary study area includes forest inventory data as well as a variety of administrative information (Table 3.1). The spatial data is transferable into a set of themes that are used in the LP-based forest planning model to represent the land base. This transfer is done by combining a variety of information into individual fields. Each theme represents a characteristic by which a stand could be identified. Combining a set of unique theme characteristics creates a development type. When age is added to a development type it becomes a development type class. There are 22 yield curves to which a stand could be classified within based on the cover type of the stand.

The extended study area is used for the fire modeling (Figure 3.2). This study area was needed to be able to mimic fire spread into and out of the primary study

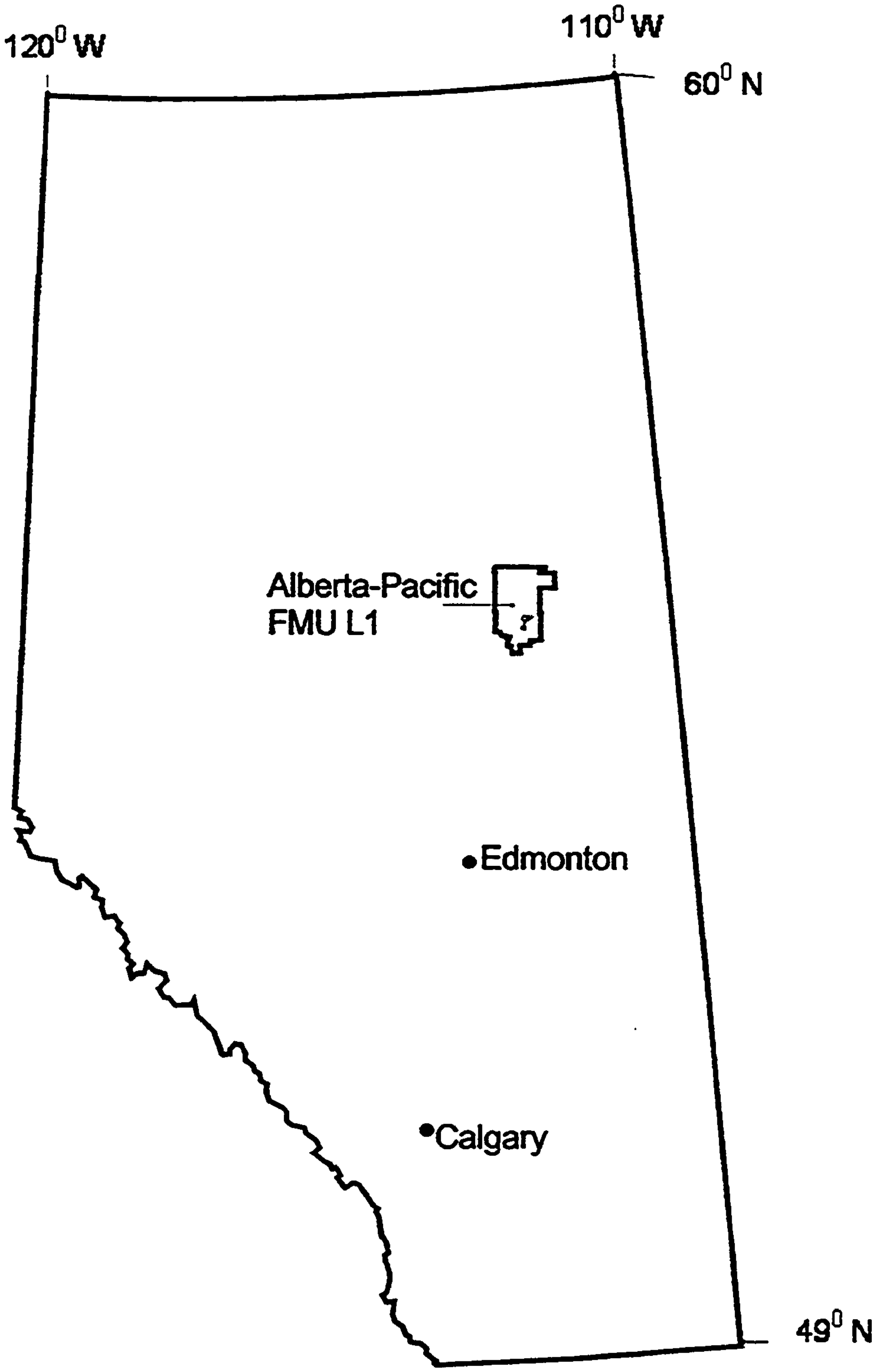


Figure 3.1. Map of Alberta showing the primary study area, in which the LP-based forest planning model and spatial harvest allocation were conducted.

Table 3.1. Theme levels and information from the LP-based forest planning model.

Alberta-Pacific					
Theme	Classification	Options	Theme	Classification	Options
1	FMU	5	5	Land base exclusions	6
	- L1a			- Provincial parks	
	- L1b			- Permanent sample plot buffers	
	- L1c			- No exclusion	
	- L1d			- Grazing reserves	
	- L1e			- Outside FMA	
2	Land base	4		- Protected notation	
	- Coniferous land base		6	Land base exclusions	16
	- Deciduous land base			- Fire	
	- Post Fire land base			- Oil and gas	
	- Undetermined land base			- Slope greater than 45%	
3	Cover Type	26		- Non-forested vegetated	
	- Aw-comp			- Non-forested disturbance	
	- Aw-S-O			- Non-forested clear-cuts	
	- Aw -S-C-S			- Anthropogenic non-vegetated	
	- Aw-Pj			- Anthropogenic vegetated	
	- AwS-S			- Naturally non-vegetated	
	- MxPj			- Unproductive index	
	- Saw-S			- Unproductive stand density	
	- Lt			- Larch component	
	- Sw-O			- Unproductive site index	
	- Sw-C-FM			- Isolated stands	
	- Sw-C-G			- Caribou habitat	
	- Sb-O			- No exclusion	
	- Sb-C-FM		7	Land base exclusions	2
	- Sb-C-G			- Water buffer	
	- Pj-O-C-FM			- No buffer	
	- Pj-C-G		8	Planning unit	2
	- Aw-U-FM			- j	
	- Aw-U-G			- non	
	- Aw-S-U-S		9	Fire Flag	42
	- Naturally non-vegetated			- 1	
	- Non-forested vegetated			- 2	
	- Anthropogenic vegetated			- 3	
	- Anthropogenic non-vegetated			- 4	
	- Non-forested disturbances			- 5	
	- Non-forested clear-cuts			- 6	
	- Area outside the FMA			- 7	
4	State	7		- 8	
	- 'A' density stands			- 9	
	- 'A' density in second rotation			- 10	
	- Delayed state			- ...	
	- Natural state			- 39	
	- Non successful regeneration			- 40	
	- Regeneration state			- burnt	
	- No status			- non	
				Possible development type	**58,705,920**

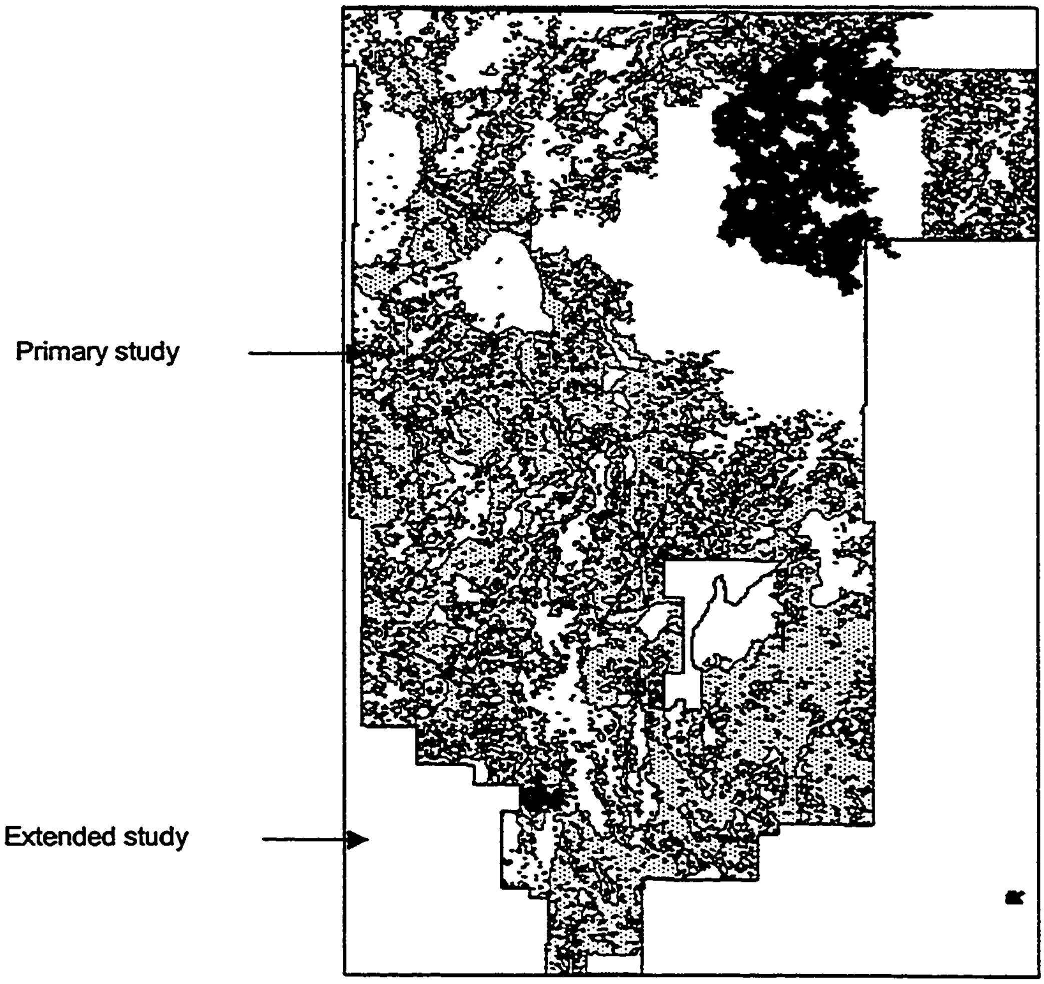


Figure 3.2. The primary study area is the Alberta-Pacific is FMU L1, and the extended fire area used for fire modeling. Black areas represent burnt areas from a 75 percentile burnt year.

area. The extended study area is created by overlaying a rectangular grid of 3 hectare hexagons over FMU L1. To create consistency between the fire model, the LP-based forest planning model and the spatial harvest allocation, the primary data set is also converted to 3 hectare hexagons. This is completed by first converting the hexagon grid to centroid points, which represent the center of the hexagons. The centroid points were then overlayed onto the polygon, primary, data set and the centriod points then take on the data from the polygons which they are within. The centroid data is then transferred back to the hexagon. This reduced the overall number of polygons in the primary study area from 131,000 to 111,000.

The distribution of forest types and ages are similar between the two data sets. Figure 3.3 shows the starting age class distribution of the hexagon and polygon data sets from the primary land base. There is no data available at the time of the study for the extended study area. Therefore inventory data is randomly assigned based on the distribution of forest types from the primary study area. This produced similar distributions of forest types inside and outside the primary data set. The main difference is that the distribution of the forest types outside of the primary data set do not have a clumped distribution like the primary data set.

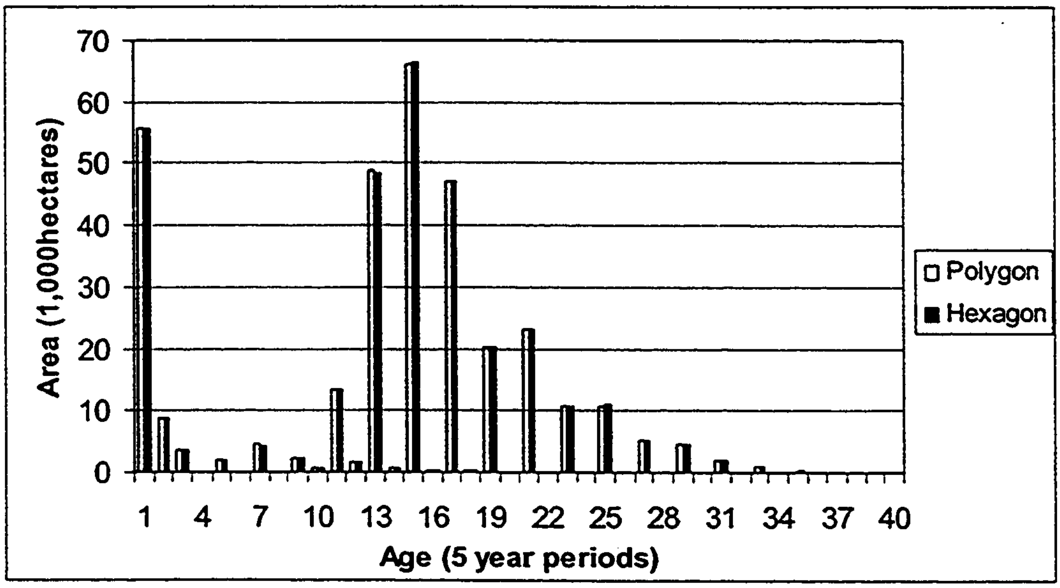


Figure 3.3. The starting age class distribution of the primary land base. Showing the distribution of the original polygon, and the hexagon age classes.

All of the non-operable data is removed from the primary data set leaving only the operable land base data for the LP-based forest planning model and spatial harvest allocation. This reduced the number of polygons within the primary data set from 111,000 to 45,000. Overall this reduced run times as less data was being carried between runs.

3.3 Methods

The methods section is broken down into four sections. The first section describes the scenarios that were analyzed in this study. The second section describes the LP-based forest planning model and spatial harvest allocation procedure used. The third section describes the fire model that was used. The final section describes how the LP-based forest planning model, spatial harvest allocation and fire model were integrated for the sequential re-planning simulations. All of the modeling in this study is done using 5 year periods.

There were four salvage policies analyzed in this study (Table 3.2). The four policies were created by varying two policy considerations. The first policy consideration was whether or not post-fire areas were assumed to regenerate immediately. Historically, in Alberta, salvage policy assumed post-fire areas did not immediately regenerate. Therefore in subsequent AAC determinations the post-fire areas were removed from operable land base, until surveys showed the areas were sufficiently restocked. After the areas were shown to be sufficiently restocked they were normally reincorporated back into the operable land base. For modeling purposes this policy option was implemented by removing post-fire areas from the productive land base for 4 periods, or 20 years. Subsequently the fire areas were reincorporated into the productive land base as one period old stands. The second regeneration option corresponds with more current policy in Alberta, where FMA holders can regenerate post-fire areas and maintain the areas in their productive land bases. For modeling purposes this regeneration option was implemented by, immediately post-fire, transitioning the existing stands to one period old stands that were assumed to regenerate post-fire.

Table 3.2. Policy options analyzed creating the 4 scenarios which were examined in the study.

	No Regeneration	Regeneration
Burnt wood is quota free	NN	RN
Burnt wood counts towards AAC	NA	RA

The second policy consideration was related to the manner in which volume salvaged from post-fire areas was accounted for. Alberta government policy has historically, and still, does not require FMA holders to count volume salvaged towards their AACs. Therefore under this policy option FMA holders, in any year, are able to harvest their entire AAC in green wood, and additionally harvest any volume salvageable from burnt areas. Therefore the harvest level attainable from the land base in any year was the AAC combined with the volume salvaged in that year. This was modeled by allocating the entire AAC in unburnt areas, and calculating the amount of volume assumed to be salvaged from post-fire areas and combining these two harvest levels. The second option, for this policy consideration, counted salvaged volume against the AAC. Therefore the harvest level in any year was equal to the AAC. This was modeled by scheduling the AAC in both burnt and unburnt areas. By combining the two regeneration options and two harvest accounting options the 4 policy scenarios analyzed in this study were created. In all scenarios volume in post-fire areas did not count toward the growing stock on the land base.

When volume salvaged from post-fire areas was not counted against the AAC different percentages of the burnt volume were assumed to be harvested. Some burnt areas may be inaccessible or otherwise unharvestable. Therefore assuming all volume burnt was salvaged would have been inaccurate. The percentage of burnt volume salvaged from post-fire areas varies depending on many factors including location, size of the timber and amount of volume burnt. These factors vary from fire to fire therefore it is difficult to determine the percentage of burnt volume that would be salvaged from any fire. To account for this variability three percentages of burnt volume salvaged were analyzed; 100%, 75%, and 50%. With these 3 calculations it would be possible to extrapolate the results to other salvage percentages.

LP-based forest planning model

The LP-based forest planning model used for this study was obtained from Alberta-Pacific and was modified as little as possible. The model needed to be modified to include the transformation from the polygon data set to the hexagonal data set, to minimize optimization times, and to allow the sequential re-planning simulations to be completed. The transformation from the polygon data set to the hexagon data set was completed to ensure consistency between the fire model and LP-based forest planning model. The modifications to the model to minimize the run times included the removal of administrative tracking data, which were not necessary for this study.

The LP-based forest planning model followed guidelines set out by the Alberta Government for the creation of forest planning models (Alberta Sustainable Resource Development, 1996, 1998a, 1998b). The objective function was the maximization of total volume, both softwood and hardwood, harvested over the planning horizon, which was 200 years. Even flow constraints were placed on both the softwood and hardwood volume harvested from the land base for the entire planning horizon. There was also an ending inventory constraint placed on the model. The ending inventory constraint took the form of a non-declining yield of the growing stock on the land base over the last half of the planning horizon. Combined these constraints ensured the model followed the sustained yield principle when scheduling activities. This model was created and run through Woodstock (Remsoft, 2003a), and optimized using Mosek (Mosek ApS, 2002).

After an area died, or was scheduled for harvest the area was assumed to transition from the existing stand to a new stand. The transitions defined in the LP-based forest planning model meant that the model did not meet the criterion of a standard model II forest planning model formulation (Johnson and Scheurman, 1977). The transitions in the model meant the model followed the generalized model II formulation of a forest planning model as described by Remsoft (2003b). The difference between the model formulations is that a generalized Model II formulation allows transitions not only from harvest, but from harvest, death, or silvicultural activities (Remsoft 2003b). Also a generalized Model II allows stands to transition to non-zero age classes.

The transitions in the LP-based forest planning model were modified slightly from those defined by Alberta-Pacific in the original model. The main change from the original model was that the leading species stayed constant in all transitions. This was a necessary change to make it possible to simulate all of the fires prior to the sequential re-planning simulations. This change to the post disturbance transitions was only necessary in a few cases. All of the other transitions were maintained as defined by Alberta-Pacific.

The Alberta-Pacific model was created using a generalized Model II timber harvest formulation (Remsoft, 2003b). For the purpose of simplicity the following model explanation shows a standard model II formulation (Johnson and Scheurman, 1977). The models used closely followed that of Armstrong and Cumming (2003), which used notation similar to Dykstra (1984, p.130-137). The objective function was:

$$\max Z = \sum_{i=1}^{D} \sum_{k=1}^{H} \sum_{j=-M+1}^{k-N} \sum_{r=1}^{P} c_{ijkr} x_{ijkr}$$

where

Z = the value of the objective function,

D = the number of timber development types,

H = the number of periods in the planning horizon,

N = the minimum number of periods between harvests,

x_{ijkr} = area (ha) of forest in development type i, born in period j, harvested in period k, managed under regime r,

M = age of oldest existing timber type, in periods,

P = the number of management regimes, and

c_{ijkr} = objective function coefficient associated with harvesting in period k, forest in development type i, managed under regime r, that was born in period j.

The model was optimized to maximize the total volume harvested (m^3) over two hundred year planning horizon. There were two harvest options available, clearcutting and understory protection harvesting.

The starting inventory was set as a constraint on the model to ensure the entire forest area was set to either a harvest or no harvest option.

$$\sum_{k=1}^{H} x_{ijkr} + u_{ij} = A_{ij}$$

$$i = 1,2,\ldots,D; j = -M+1,-M+2,\ldots,0; r = 1,2$$

where

A_{ij} = initial area (ha) of development type i born in period j, and

u_{ij} = area (ha) of forest in development type i born in period j that is never harvested in the planning horizon.

Area constraints were placed on the model to ensure that area harvested stays within the planning problem.

$$\sum_{i=1}^{D}\sum_{k=1}^{H-1}\sum_{r=1}^{P}x_{ikr}+u_{ik}=\sum_{i=1}^{D}\sum_{m=k+1}^{H}\sum_{r=1}^{P}x_{imr}+u_{im}$$

Even flow constraints were placed on the model as separate constraints on both the softwood and hardwood volume.

$$S_k=\sum_{i=1}^{D}\sum_{j=-M+1}^{k-N}\sum_{r=1}^{P}s_{ijkr}x_{ijkr}\qquad k=1,2,\ldots,H-1$$

$$S_k-S_{k+1}=0\qquad k=1,2,\ldots,H-1$$

$$D_k=\sum_{i=1}^{D}\sum_{j=-M+1}^{k-N}\sum_{r=1}^{P}h_{ijkr}x_{ijkr}\qquad k=1,2,\ldots,H-1$$

$$D_k-D_{k+1}=0\qquad k=1,2,\ldots,H-1$$

where

S_k = softwood volume (m^3) harvested in period *k*,

s_{ijkr} = softwood harvest volume (m^3ha^{-1}) associated with development type *i*, birth period *j*, harvest period *k*, and managed under regime *r*,

D_k = hardwood volume (m^3) harvested in period *k*,

d_{ijkr} = hardwood harvest volume (m^3ha^{-1}) associated with development type *i*, birth period *j*, harvest period *k*, and managed under regime *r*.

In addition to the constraints used by Armstrong and Cumming (2003) an ending inventory constraint was placed on the model. This growing stock constraint ensured that the inventory did not decline over the second half of the planning horizon.

$$G_k=\sum_{i=1}^{D}\sum_{j=-M+1}^{k-N}\sum_{r=1}^{P}g_{ijr}x_{ijr}+g_{ijr}u_{ijr}\quad k=H/2,H/2+1,\ldots,H$$

$$(1-\alpha)G_k-G_{k+1}\leq 0\quad k=H/2,H/2+1,\ldots,H-1$$

where

G_k = total volume (m^3) on the land base in period *k*,

g_{ijr} = growing stock volume (m^3ha^{-1}) associated with development type *i*, born in period *j*, managed under regime *r*,

α = maximum proportional increase in growing stock from one period to the next, and

Nonnegativity constraints were applied to all activities within the model to ensure that they all occur at positive levels.

$$x_{ijkr} \geq 0;\ u_{ij} \geq 0;\ S_k \geq 0;\ D_k \geq 0;\ G_k \geq 0;\ \forall i, j, k$$

LP-based forest planning models, as previously discussed, normally aspatially schedule harvest on a defined land base. It was not possible to spatially allocate the entire harvest scheduled by the LP-based forest planning model without violating operational ground rules set out by the Alberta government. These operational ground rules include constraints on block size and adjacency of blocks prior to green-up delay. Green-up defines the amount of time that must pass before a block can be scheduled next to a previous block. In this study the spatial allocation of the LP-based forest planning model solution was completed using Stanley (Remsoft, 1999). Stanley uses a Monte Carlo optimization heuristic to allocate harvest onto the land base over the specified period of time.

Prior to using Stanley to spatially allocating the LP-based forest planning solution there were numerous inputs required. These inputs include a minimum block size constraint which was set to 3 ha. The maximum block size was set to 300 ha, and target block size was set to 75 ha. The block size parameters were defined based on the historical distribution of blocks on the land base. The green-up delay was set to 3 periods, or 15 years. Alberta-Pacific uses a green-up delay of 20 years for coniferous blocks and 10 years for deciduous blocks (Alberta-Pacific, 1999). A 15 year green-up delay was set as a compromise as it was only possible to define one green-up delay in Stanley. The proximal distance was set to 0 meters for this study. Proximal distance represents the distance two blocks can be apart and were still considered next to each other. This means blocks separated by roads or cutlines, if less than the proximal distance were still considered next to each other. The proximal distance was set to 0 as the hexagonal grid meant that there were no features such as roads in the data set that required the use of proximal distance. It was also necessary to define all of the areas that had been harvested within the previous 3 periods so that Stanley did not schedule harvest next to these areas until they had reached the green-up delay age. These user defined blocks that Stanley must schedule around are called pre-blocks. There was a 10% fluctuation of harvest allowed between periods. This fluctuation was necessary due to the manner in which Stanley allocates harvest making it difficult, if not impossible, to schedule identical harvest levels from period to period.

Stanley spatially was set to allocate the LP-based forest planning model solution for the first 10 periods in this study. When a Stanley run was started the initial step undertaken by Stanley was the creation of blocks. Stanley groups adjacent polygons on the land base into blocks, based on the user inputs. Stanley also allows the user to define the distance polygons can be apart and still be grouped together; in this study adjacency distance was set to 0. After Stanley blocks the land base it randomly allocates the blocks into a harvest period, to try to achieve the LP-based forest planning model solution. After randomly allocating the blocks into specific periods Stanley then evaluates the allocation by comparing the harvest level it has spatially allocated to the harvest level scheduled by the LP-based forest planning model. Once the allocation has been evaluated, Stanley then re-allocates the blocks into a new spatial allocation, and evaluates this new spatial allocation. If the new spatial allocation was better than the previous best solution it is kept as the best solution, and all other solutions were deleted. This procedure was repeated a large number of times and the best solution was then reported as the optimal solution at the end of the run time. Stanley was run for 3 minutes for all simulations in this study. It was found through preliminary runs that the best solution Stanley found was normally identified within the first 2 minutes. One minute extra was added to allow for more complicated model situations, while still finding the best solution possible.

Fire Model

The fire model used in this study was based on Feng's (2004) MSc thesis. The model was created for a study area within the same general location. The fire model was based on the cellular automata theory, and used a hexagonal grid. Each of the hexagons in the study area had 6 equidistant neighbors. Neighbors represent hexagons that share a similar boundary area. The creation of a single fire was a fairly simple process after all of the data preparation was completed (Figure 3.4). Two tables were required to simulate fires, one containing the cells neighbors and the other containing the land use and species information of each hexagon. A toroidal shift was completed on the edges of the grid, this meant the top of the study area was connected to the bottom and the right side was connected to the left side. A toroidal shift allowed the ability to mimic the effect of fire spreading into the study area from outside. The extended study area represented the smallest area in which a toroidal shift could be completed on. This was because it was only possible to complete a torodial shift on a symmetrical shape. Prior to the creation of each fire a random wind speed and direction were drawn from a historical distribution of weather data. With the species information and weather data it was possible to calculate a probability of a cell burning. The probability of a cell burning was indirectly affected

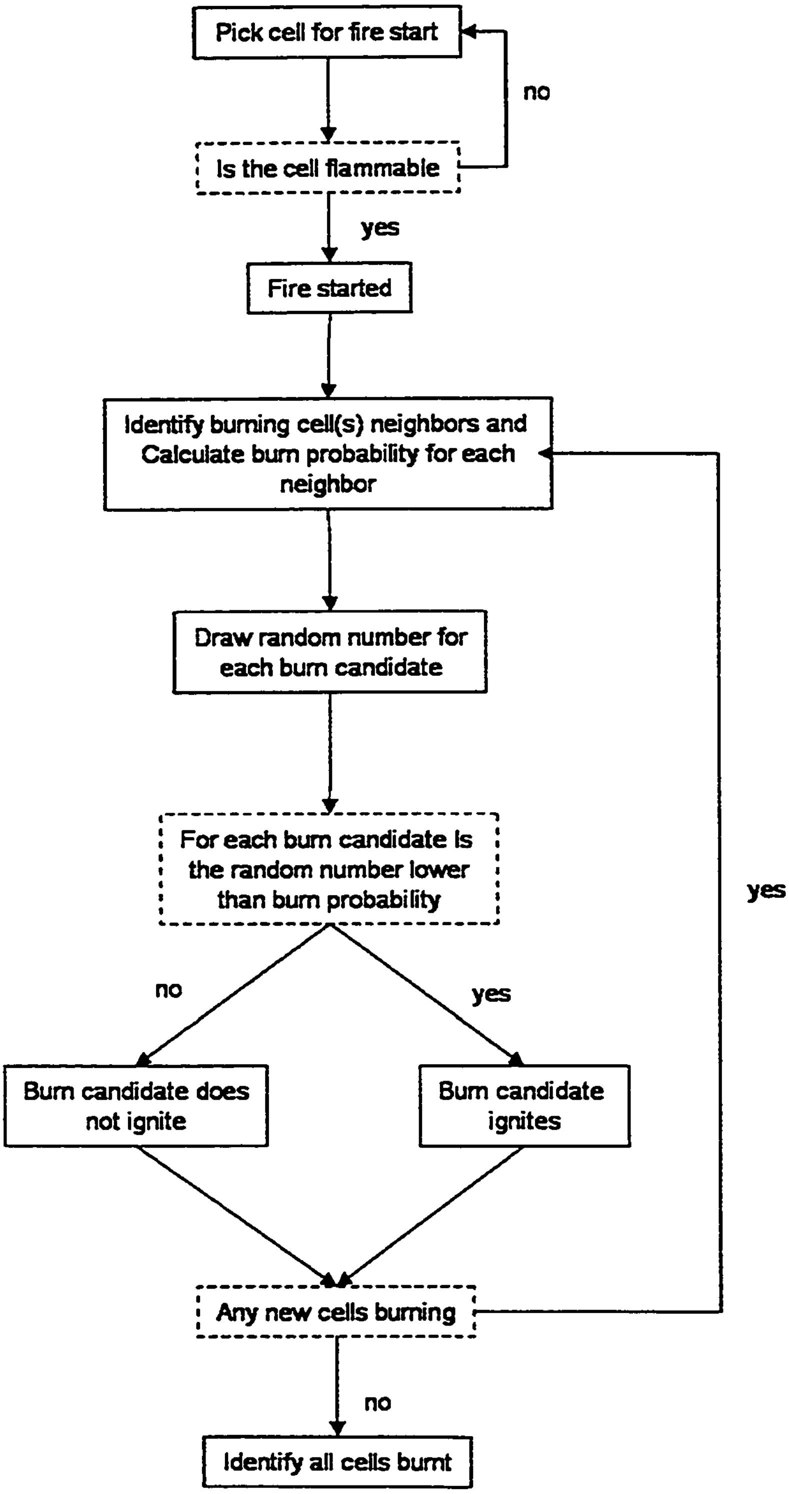


Figure 3.4. A flowchart showing the steps to create a fire based on the model created by Feng (2004).

by the number of neighboring cells. Table 3.3 shows the probabilities of species burning based on the work of Cumming (2001). Wind speed and direction affected fire based on the spread effects from Hargrove et al. (2000), and were altered by Feng (2004) for the hexagon fire model (Figure 3.5).

Table 3.3. Species specific annual burn probabilities from Cumming (2001).

Fuel type	Aspen	White spruce	Black spruce	Pine	Other
Burn rate (%)	0.05	0.17	0.5	0.42	0.17

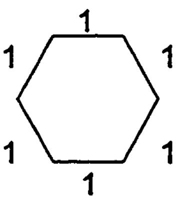
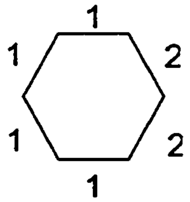
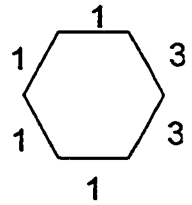
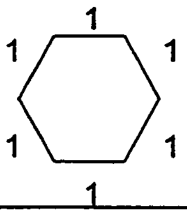
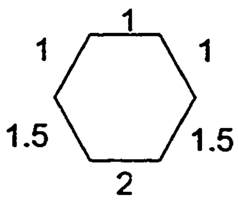
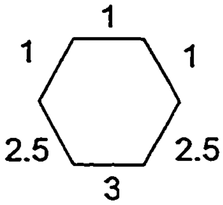
Wind Direction	Wind Speed		
	Weak (≤3km/h)	Moderate (4 to 22km/h)	Strong (≥22km/h)
West Wind			
North Wind			

Figure 3.5. Effect of wind speed and direction on spread from Feng (2004).

The first step in the creation of a fire was randomly selecting a cell for the fire start location. If the fire was not of a flammable type a different cell was selected until a flammable cell was selected. With the fire start cell identified all of the neighboring cells were drawn from the cell neighbors table. For each of these cells the species information was drawn from the land use table. With the species and weather information identified burn probabilities were calculated for each of the neighbors. A random number was then drawn for each of the neighbors. If the random number was lower than the burn probability then the cell was assumed to start burning. For each of the cells that started burning this process was repeated until no new cells start burning. The process creates a single fire on the land base. After a fire was created the cells that burnt in that fire were stored to a database identifying the period in which they burnt. To create the series of fires it was necessary to execute the above fire model for each fire assumed to burn. The number of fires burnt in a period was calculated by summing 5 random draws from the historical fire data for the study area from 1940 to 2003 (Figure 3.6). This process was completed for 20 periods and all of the information was stored to a fire database. It was possible to run all of the fires prior to the sequential planning simulation as the model was age independent, and the primary species of each stand stayed constant through time.

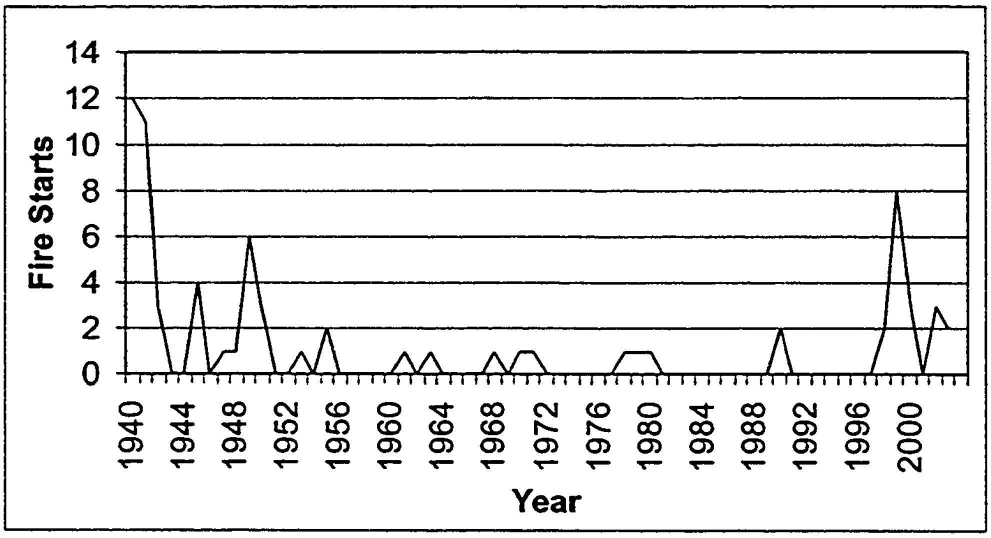


Figure 3.6. Fire starts in the study area between 1940 and 2003.

Implementation of the sequential re-planning simulations

Prior to running the sequential re-planning simulations, some modeling and data manipulation was completed to reduce run times. The data manipulation completed prior to the simulations included the modification of the Woodstock and Stanley models to remove any unnecessary information while maintaining the models as close to originals as possible. For the Woodstock model this involved removing any variables and outputs that were not relevant to the maximization. The outputs and variables removed were unnecessary as they were created for model verification and land base tracking but were not needed after the model was finalized. In the Stanley model all of the polygons that were not operational were removed from the land base. This removal of non operable land base did not affect the spatial allocation or fire modeling, as all of the fires were run prior to any spatial allocations and the removal of this non operable area.

To implement the sequential re-planning scenarios it was necessary to transition the forest forward by five years prior to each recalculation of the AAC. As was previously discussed sequential re-planning scenarios involve re-determining the AAC at set intervals for a defined length of time to estimate the change to the harvest level through time. Completing sequential re-planning simulations using different assumptions or incorporating stochastic events, such as forest fires, allows the effect of these changes from scenarios not including these events. In this study the AAC was re-determined every 5 years for 100 years, or 20 periods. In this study every AAC determination is referred to as a run. The combination of the 20 runs is referred to as an iteration. For each of the different scenarios completed multiple iterations were completed. Multiple iterations were completed to capture a range of possible outcomes. There were different possible outcomes as there were stochastic events in all of the scenarios.

There were 100 iterations completed in the 4 salvage policy scenarios, and only 10 iterations completed in the base case. Numerous iterations were required to capture the variations in harvest level from the different burn rates, and stochastic harvest allocation procedure used. A reduced number of iterations were used in the base case as there was no fires in these simulations. The only stochastic effect in the base case was from the Monte Carlo simulations in the Stanley runs. Without stochastic factors each iteration would be identical, therefore multiple runs allowed the effect of these stochastic effects to be captured, as there is an increase in the stochastic effects on the forest area it was necessary to increase the number of iterations to capture the distribution.

Prior to running the simulations it was necessary to save the original shape file. This was necessary to ensure that all of the iterations started with the same starting land base information.

Each iteration started by calling a Matlab script, referred to as script *a*, which incorporated fires into the spatial land base information, for the salvage policy scenarios, and also created an output file summarizing the land base (The MathWorks Inc, 2002). This land base summary was in the format required by Woodstock. With this land base file Woodstock was called to create an LP matrix. This LP matrix was them solved using Mosek. Woodstock was then called to report on the LP solution. With the Woodstock model optimized these results and the spatial land base information were used by Stanley to spatially allocate the Woodstock optimal solution. The completion of the spatial allocation by Stanley was the end of the first run in an iteration. Before the second run, or year 5 AAC could be optimized it was necessary to age the forest by 5 years, and in the scenarios which required it, incorporate fires onto the land base. This aging of the forest was completed using a second Matlab script, referred to as script *b*. This script increased the age of the entire forest by 5 years, reset the age of any stands that were scheduled for harvest by Stanley, and any stands that were assumed to burn. This script ended by creating a land base file that could be read by Woodstock. Prior to starting the next run the Woodstock and Stanley solution files were saved to disk. After saving the files the next run was started by calling Woodstock to create a LP matrix. This entire process was completed 20 times which represented an iteration. After each iteration was completed all of the files where changed back to the original files so the next iteration started at the same level. This process was automated using a Windows batch file. The batch file was created using two loops, the outer loop cycled through the iterations and the inner loop cycled through the runs within an iteration.

```
for 1 – 100 {iterations}
    Call Matlab script a
    for 1 – 20 {runs}
        Call Woodstock
        Call Stanley
        Call Matlab script b
        Save Woodstock and Stanley outputs
    end
    Revert to original files
end
```

Script *a*, which was the initial step in each iteration, was used for a number of purposes. First it incorporated fires into the land base information, in all but the base case scenario. This was completed by querying on the fire database for all areas burned in the first period. All areas affected by fire in the first period then had their land base information changed to represent the change in there stand state. This was done using theme 9 in this study. In the cases where salvage volume was not counted against the AAC the script completed a calculation of the volume of wood that was burnt in the period. The result of this calculation was then written to a salvage database used to store this information. Finally script a summarized the land base information into an area file summarizing the land base in an aspatial format used by Woodstock.

The second Matlab script, *script b*, was more involved. The first process in this script was the same as the previous Matlab script, this queried the fire database to find all areas that burned in the period of the current run. Script *b* then identified all areas that had been harvested within the previous 15 years, or 3 periods, referred to as pre-blocks by Stanley. These areas represent areas that can not be harvested next to based on the rules defined in Alberta-Pacific's DFMP. This process was completed by first clearing all pre-block identifiers from the previous run. Subsequently all stands harvested in the previous 3 periods were queried and a pre-block identifier was added to their spatial information. The forest was then aged by increasing all of the stand ages by one period, or 5 years. Next all of the stands that were scheduled by Stanley to die, or be cut were queried and their spatial information was updated to incorporate the changes to there age and stand information. These deaths include stands that are at the end of regeneration and fire delays. The fire delays were only relevant when the fire policy scenario being analyzed had no regeneration post-fire. Next the fires areas were incorporated onto the land base in the same manner as the previous Matlab script. Salvage calculations were also completed, in the same manner as script *a*, when the salvage volume was not counted against the AAC. The database information was then formatted and written to an area file readable by Woodstock for the next run.

In addition to the base case and four policy scenarios one more set of 10 iterations were completed. In this set of iterations the post-fire area was assumed to regenerate, and volume salvaged did not count towards the AAC. This scenario differed from RN scenario due to a change made to the Stanley constraints. The green-up delay in this additional scenario was set to zero years, or there was no green-up constraint place on the model. This was meant to allow more of the volume to be allocated, from the LP-based forest planning model solution, by Stanley. As was previously discussed green-up constraints have been shown to decrease the amount of volume that can be allocated onto the land base. This was completed as initial results showed some trends that could be explained with these additional iterations.

3.5 Results and Discussion

The first scenario run was the base case scenario, with no fires incorporated onto the land base. The first run in this scenario involved the optimization of the Woodstock model and the subsequent spatial allocation of the solution. When optimized the LP-based forest planning model was solved the objective function was 59.17 million m^3 over the planning horizon. Distributed evenly over the 200 years this is equivalent to an aspatial optimized harvest level of 296,000 m^3 yr^{-1}. Aspatial optimized harvest level refers to the level of harvest that the LP-based forest planning model allocated based on the objective function and constraints defined in the model. Stanley spatially allocated 87% of the aspatial optimized harvest level in the first 10 periods. In the 3 minutes Stanley was run for approximately 15,000 different possible spatial allocations where evaluated. Stanley was unable to allocate the entire volume scheduled in the LP-based forest planning model for a number of reasons. These reasons included the inability of Stanley to: break up polygons into smaller units; violate the constraints on volume flow, block size, and adjacency. As has been previously discussed the Monte Carlo heuristics does not necessarily find the optimal solution to a spatial allocation problem.

Subsequent to the completion of the first run the rest of the first iteration was completed. This process was then repeated 9 more times for the base case. Figure 3.7e shows the distribution of the aspatial optimized harvest levels from each of the 10 iterations as the runs progress through time. The distributions of aspatial optimized harvest levels were very constant level through time, with very few outliers. Though there was a slight increase in aspatial optimized harvest level initially, this was at least partially due to the spatial allocation by not allocating the entire aspatial optimized harvest level. The proportion of the aspatial optimized harvest level which Stanley spatially allocated decreased from an initial level of 87% to approximately 84% (Figure 3.8e). The decrease in percentage allocation possible by Stanley was due to the green-up delay coming into effect. Initially, no pre-blocks were defined on the land base. Therefore, in the first 3 periods, the green-up constraint became increasingly binding. This decreased the ability of Stanley to schedule the harvest over time. The spatially feasible harvest level, referred to as the AAC in this study, was calculated by multiplying the spatial allocation percentages by the aspatial optimized harvest level (Figure 3.9e). The slight decline in AAC was a function of the decline in Stanley spatial allocation percentages. Without fire it can be seen that the aspatial optimized harvest level stays fairly constant through time, while the spatial allocation percentage declined due to the increasing constraint levels. This declining spatial allocation caused a decline in the AAC.

All of the fires used for the sequential re-planning scenarios were run prior to the sequential re-planning simulations, this was possible as burn probabilities were age independent. Each of the iterations and runs had unique sets of fires created for them. Though each scenario used the same set of fires allowing a more direct comparison of the scenario iterations. All of the fire data was tracked periodically, the periodic data was divided by 5 to create approximated annual information. The distribution of fire sizes simulated showed a negative exponential form (Figure 3.10). There were a significantly lower number of large fires; however these

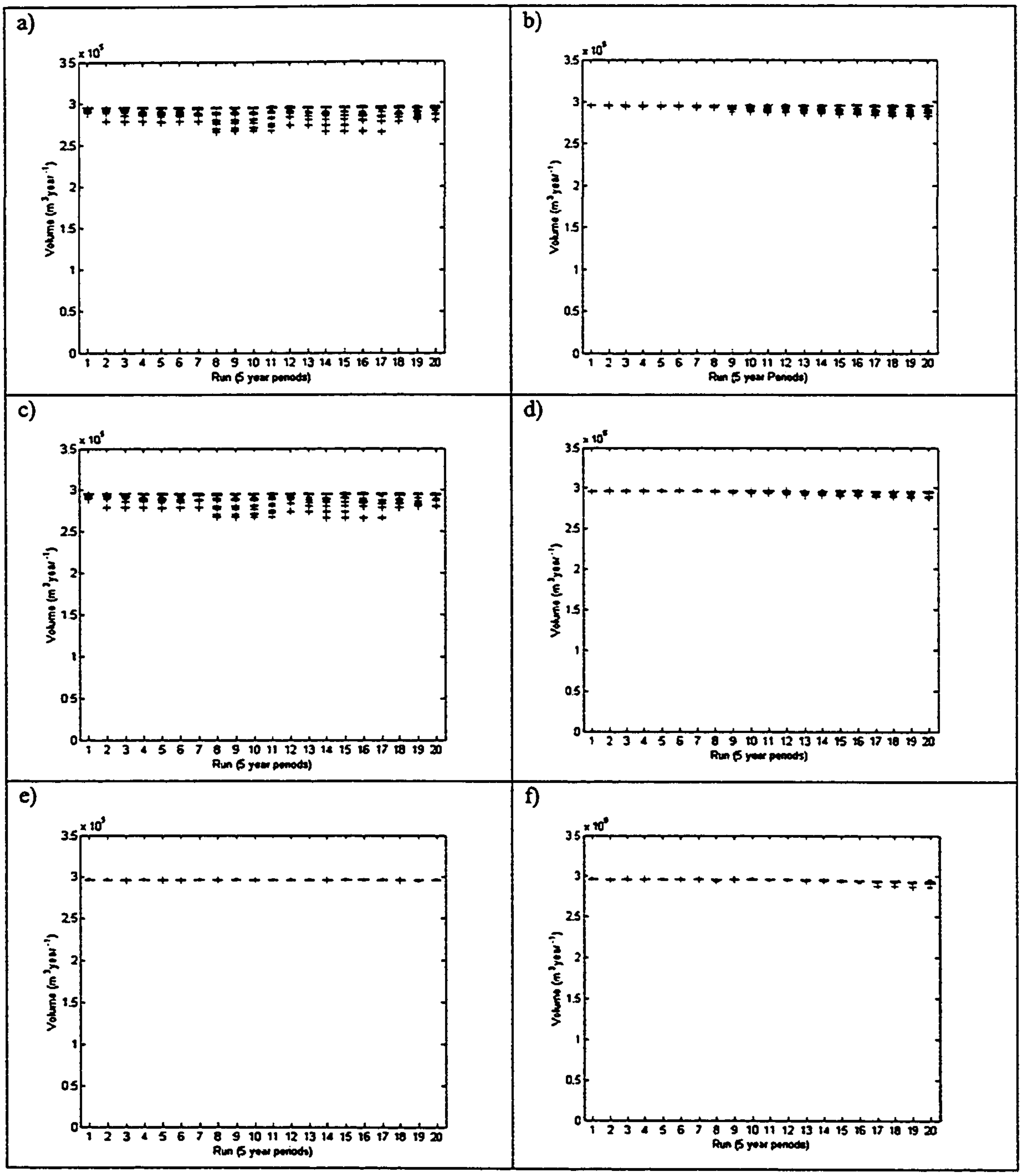


Figure 3.7. Boxplots showing the distributions of the aspatial optimized harvest levels from all of the policy scenarios. a) NN scenario b) RN scenario c) NA scenario d) RA scenario 4 e) Base case f) 0 year green-up scenario.

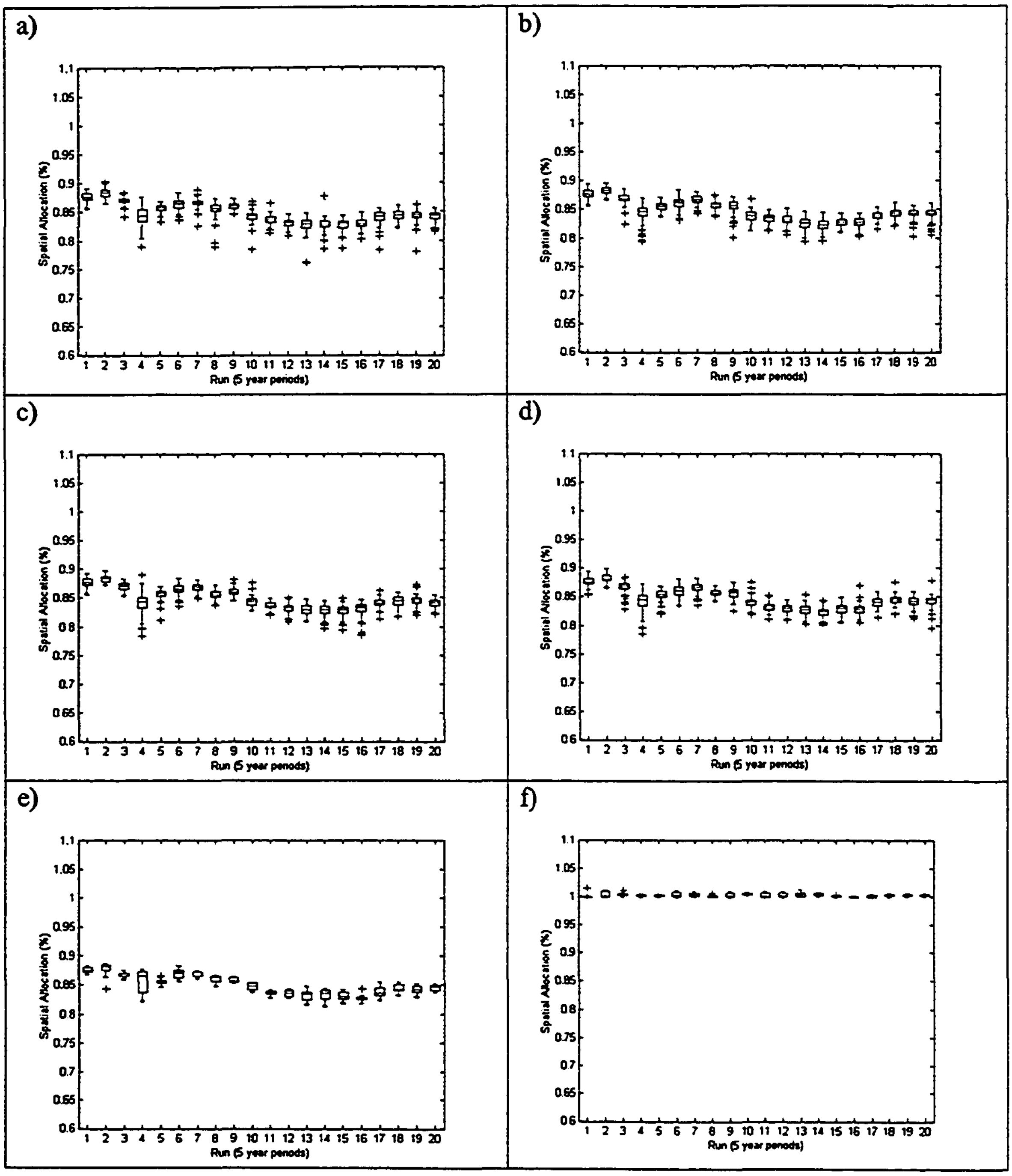


Figure 3.8. Boxplots showing the distributions of the percentage of the aspatial optimized harvest levels spatially allocated by Stanley for the runs. a) NN scenario b) RN scenario c) NA scenario d) RA scenario e) Base case f) 0 year green-up scenario.

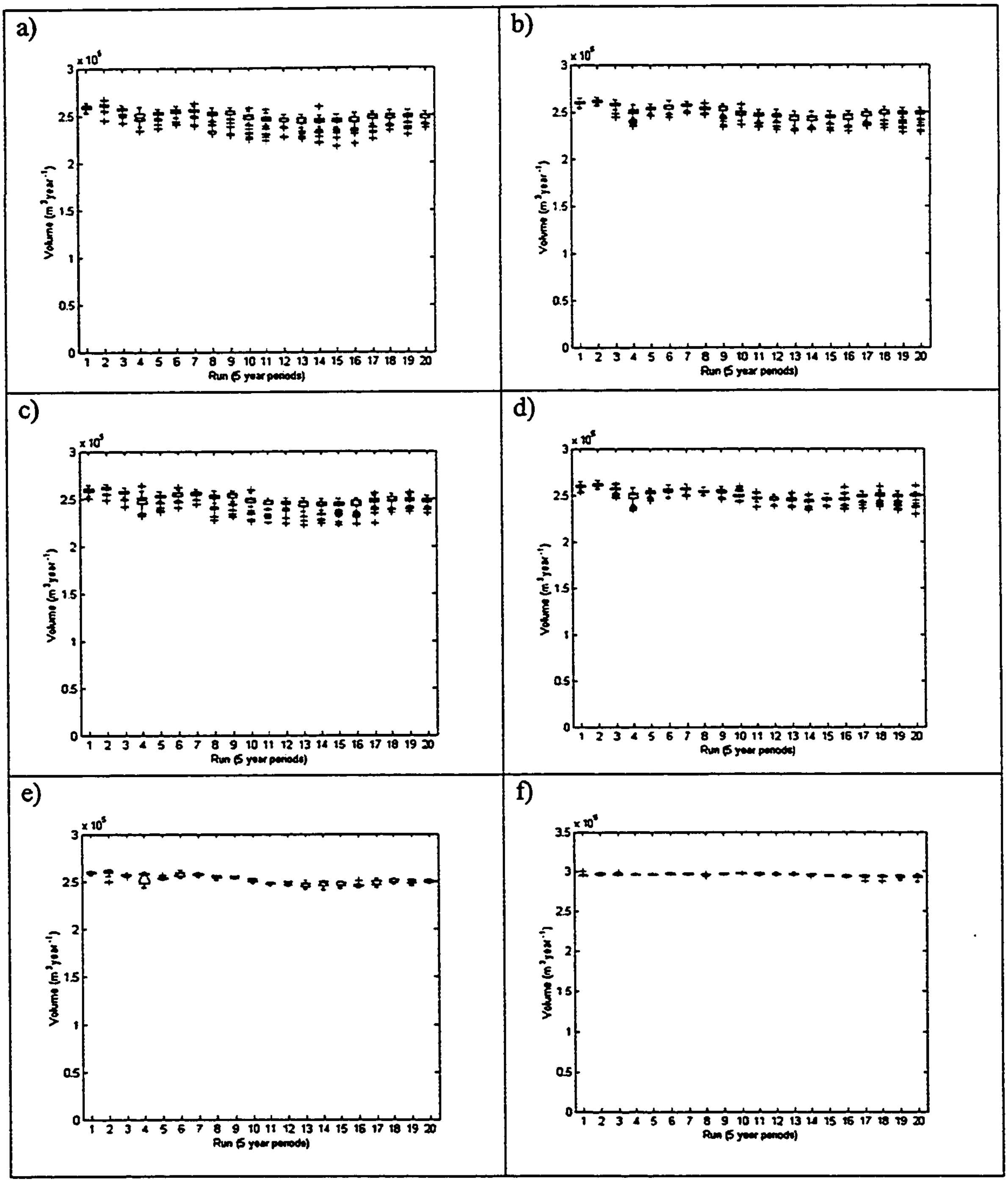


Figure 3.9. AAC's from all of the runs and cases. a) NN scenario b) RN scenario c) NA scenario d) RA scenario e) Base case f) 0 year green-up scenario.

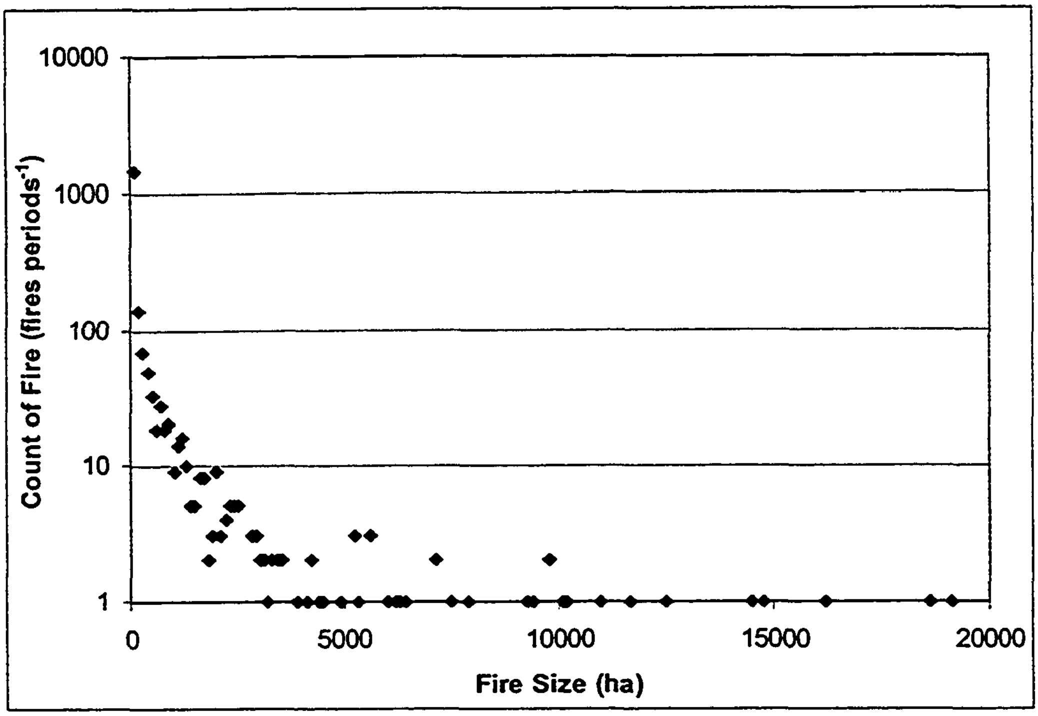


Figure 3.10. Number of fires by size from all of the fires.

large fires account for the majority of the area burnt. On average 1.6% of the forest burnt in any particular period, therefore the annual burn probability was approximately 0.32%. The annual proportional burn results broken down by species can be seen in table 3.4. For comparison the annual proportions burnt in the 2002 fire year, when the House River fire burnt in FMU L1, can also be seen in table 3.4. The annual results shown could not be assumed to be equal to the real annual burn probabilities as there was bias between the periods; some years have higher burn probabilities than others. The probabilities resulting from the fire data did not exactly match the probabilities from Cumming (2001). The results are proportionally similar between forest types but differed slightly in values. This was largely believed to be due to the small number of iterations completed. Figure 3.11 shows the distribution of fire sizes in each run. It can be seen that the majority of the runs had very little area burning on the land base. Though there were some cases where there was a large amount of area burning. There was a general trend in this study for the non operational stands to burn at higher frequencies than the operational stands. This reduced the effect of fire on the operable land base. There were no calculations done to analyze the shape metrics of the fires burnt onto the land base. The fire shapes were visually analyzed and seemed realistic; a fire period in the 75 percentile has been shown in figure 3.2.

Table 3.4. Proportions of the study area burnt annually by forest type from fire model and observed at the House River fire.

Fuel type	Aspen	White spruce	Black spruce	Pine	Other
Burn rate (%)	0.02%	0.05%	0.41%	0.33%	0.05%
House river fire	0.06%	0.05%	0.13%	0.19%	0.10%

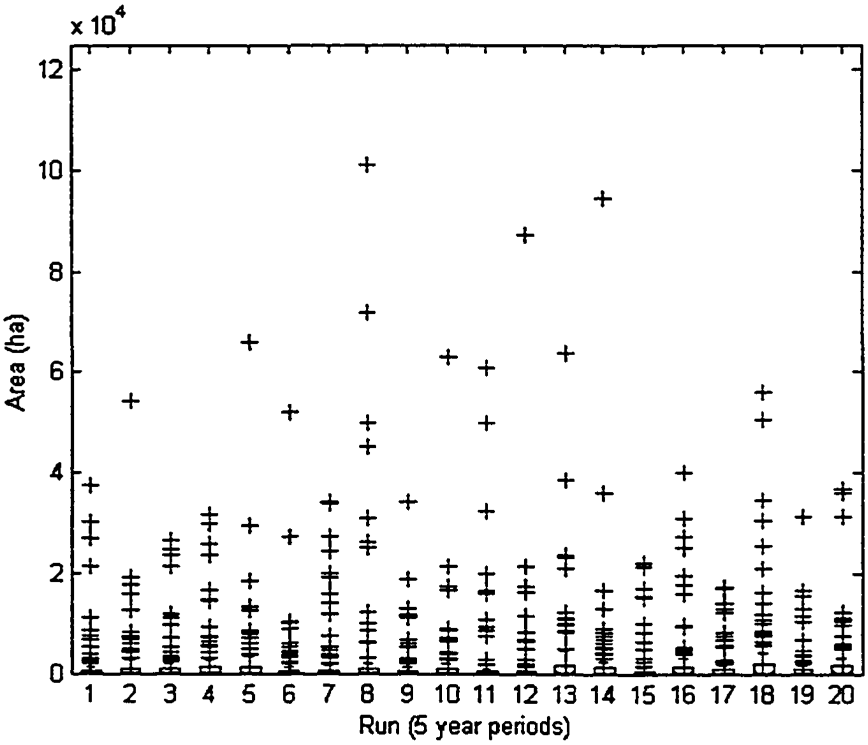


Figure 3.11. Boxplot showing the distribution of fire sizes that occurred in each of the runs.

With the base case iterations and fire simulations completed, fires were incorporated the remaining simulations to analyze the effect of different fire policies on long term harvest levels. The first scenario completed was the NN scenario, which represents the historical salvage policy used in Alberta. This scenario assumes that burned areas are removed from the productive land base and AAC determinations for 20 years and the volume harvested from burnt areas does not count against the AAC. The aspatial optimized harvest levels from NN scenario show a fairly constant inter-quartile distribution through time (Figure 3.7a). There were tails in distributions below the whiskers (i.e. 1.5 times the inter-quartile range). The main effect of including fires under the NN policy scenario was an increased number of outliers from the base case. Random iterations, of the aspatial optimized harvest level, were selected to look at trends in the individual iterations. Figure 3.12a shows that after high fire years there was a decrease in aspatial optimized harvest level for 4 periods after which the aspatial optimized harvest level then returned to the pre-fire levels. The decline in aspatial optimized harvest level was caused by the fire area being removed from the productive land base for 4 periods, post fire.

The proportion of the aspatial optimized harvest level Stanley was able to spatially allocate was similar to the base case (Figure 3.8a). However, there was a wider distribution of spatial allocation percentages, this was attributed partially to the larger number of runs completed and partially to fires being incorporated into the scenarios. Certain runs with very high levels of fire (10,000+ ha) showed a decline in the percentage of optimal allocation for a number of periods. The AAC in the NN scenario showed a decline proportional to the decline in the Stanley spatial allocation (Figure 3.9a). Volume burnt in each run varied based on the area burnt and the yield in each stand that burnt (Figure 3.13). The inter-quartile range and whiskers of volume burnt were close to zero, though there were a high number of outliers corresponding with the outliers from figure

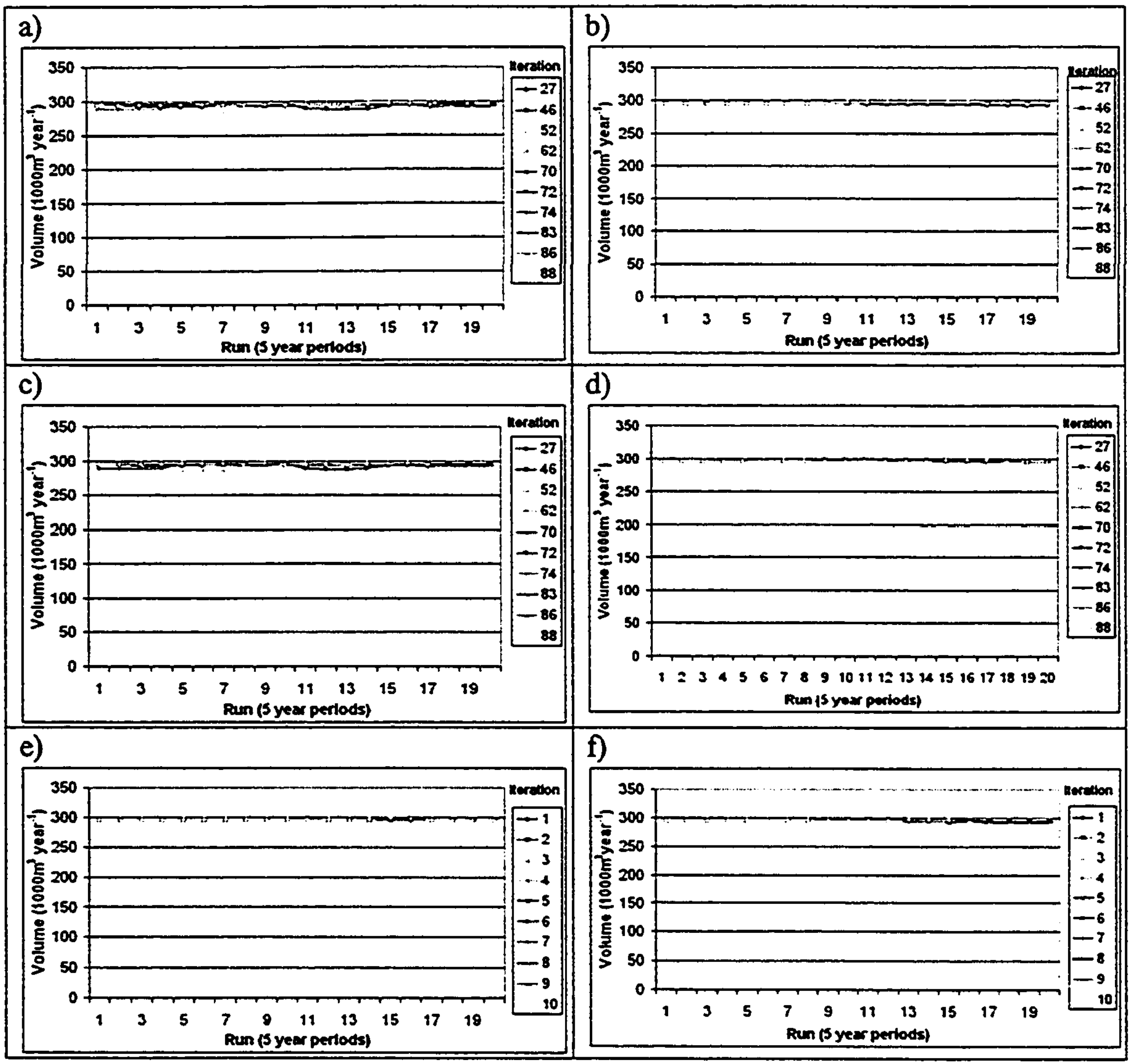


Figure 3.12. Random iterations of the aspatial optimized harvest levels through all runs. a) NN scenario b) RN scenario c) NA scenario d) RA scenario e) Base case f) 0 year green-up scenario.

3.11. Decreasing the percentage of the burnt timber that was salvaged results in a proportional decrease in the salvage volume. When the salvage volume was combined with the AAC there were a large number of positive outliers that were not present without salvage volume contributing to the harvest level. The NN scenarios showed little difference from the base case, except in extreme fire years. As the area burnt was usually low there was little change to harvest levels from the base case. When there were extreme fire years there were two effects in this scenario. The first effect was a large increase in harvest level in the current period and the next effect is a subsequent 3 period decline in the harvest level. There was only a decline for 3 periods as the salvage volume compensated for the decline in the first period.

The RN scenario differed from the NN scenario in that the post-fire areas were assumed to regenerate; therefore they stayed in the productive land base post-fire. The aspatial optimized harvest levels in the RN scenario (Figure 3.7b) were very constant with fewer outliers than the NN scenario. When post-fire land bases were assumed to regenerate the outliers that were present in the NN scenario were not present to as great of a degree. In the case of extreme fires there was still a slight decline in IHL, especially in the later periods. The effect of large fires seemed to be greater in later periods as there was less mature timber and more scarce therefore more valuable. The spatial allocation percentages were similar to the base case and the NN scenario (Figure 3.8b). The AACs declined through the runs (Figure 3.9b), this decline was a function of the declining Stanley spatial allocations. The volume salvaged was very similar to the NN scenario (Figure 3.14). The difference between the salvage volumes in the two scenarios was due to the different scheduling of activities. Adding salvage volume to the AAC increased the number of positive outliers. Overall the benefit, to FMA holders, of regenerating the post-fire areas was a reduction in the number of negative outliers in the AAC. In individual iterations this translated to the removal or reduction of the decrease in aspatial optimized harvest level for the 3 periods post fire that was present in the NN scenarios. The cost of reducing the negative outliers would be equal to the cost of regenerating the post-fire areas. In many cases this cost could be very low as many species naturally

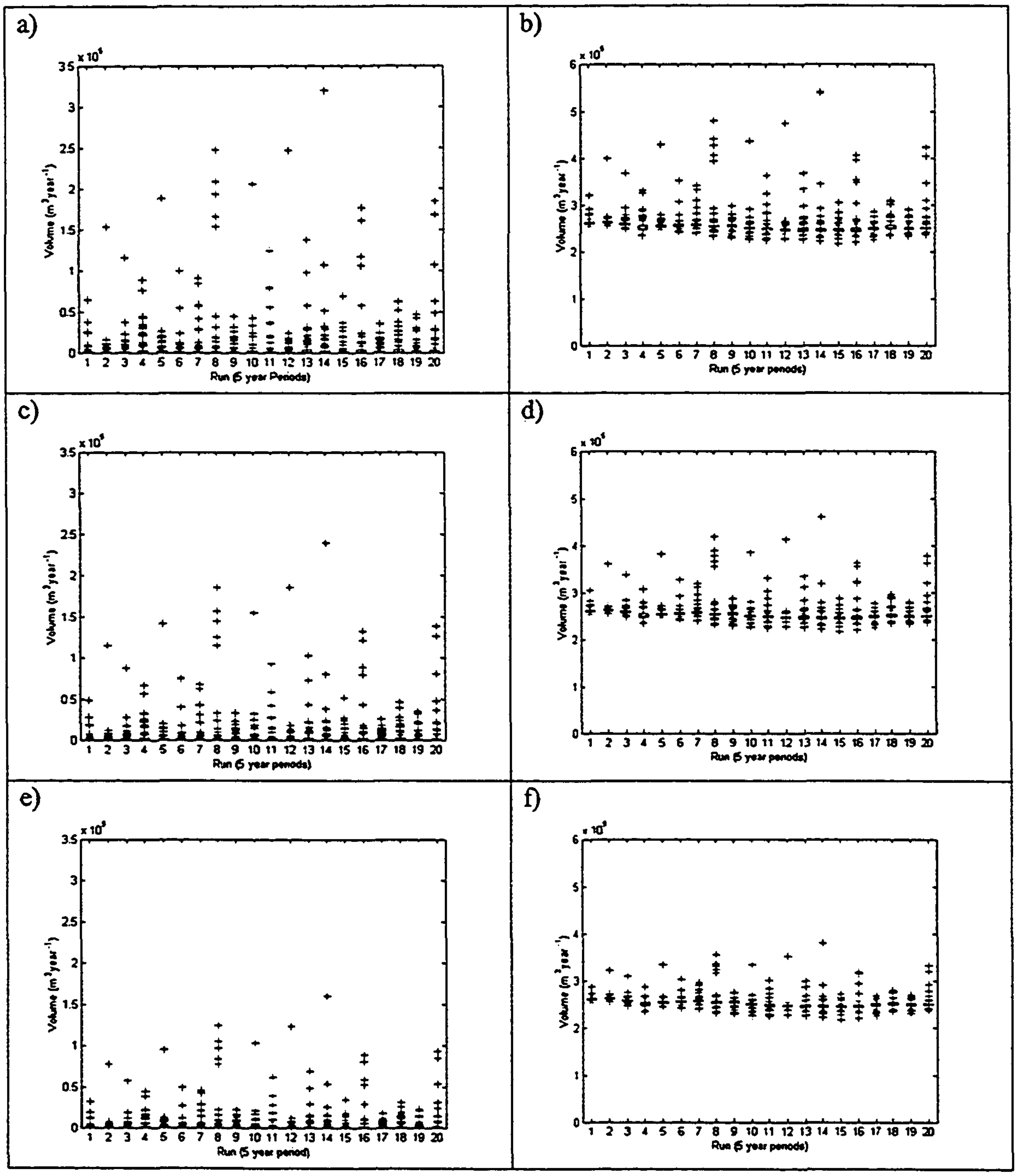


Figure 3.13. The total salvage volume, in the NN scenario, harvested under different percentages of the burnt volume salvaged and the salvage volume plus the AACcombined a) 100% burnt volume salvaged b) 75% burnt volume salvaged c) 50% burnt volume salvaged d) AAC + 100% salvage e) AAC + 75% salvage f) AAC + 50% salvage.

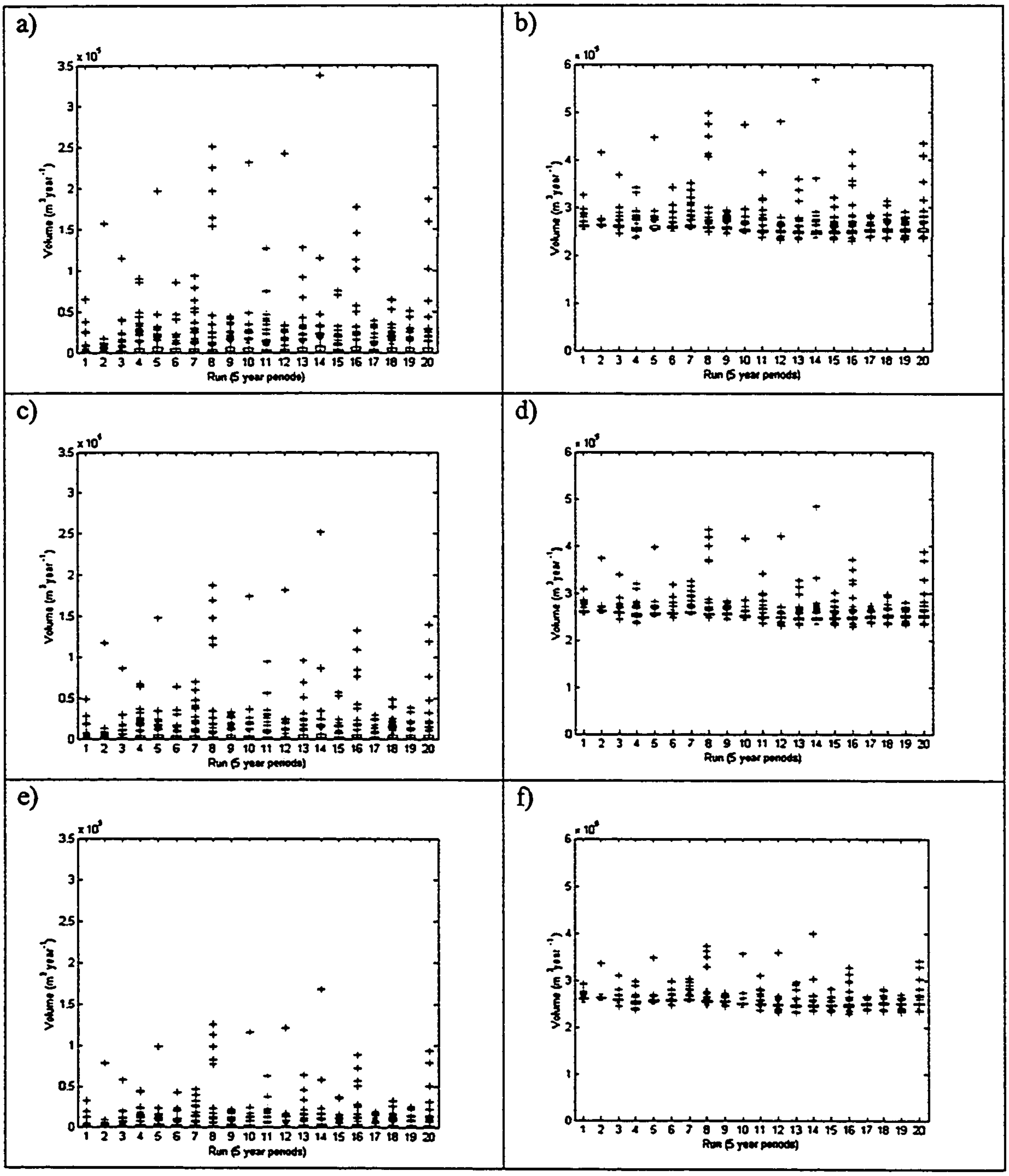


Figure 3.14. The total salvage volume harvested, in the RN scenario, under different percentages of the burnt volume salvaged and the salvage volume plus the AAC combined a) 100% burnt volume salvaged a) 100% burnt volume salvaged b) 75% burnt volume salvaged c) 50% burnt volume salvaged d) AAC + 100% salvage e) AAC + 75% salvage f) AAC + 50% salvage.

regenerate post-fire. However, if natural regeneration did not occur, the cost of regenerating extensive fire areas could be very high.

In the NA scenario there was no regeneration post-fire and the salvage volume counted against the AAC. The aspatial optimized harvest level in the NA scenario was very similar to the NN scenario (Figure 3.7c). There were numerous negative outliers associated with high fire years reducing amount of area in the productive land base for 4 periods post fire. The aspatial optimized harvest level was slightly higher in the NA scenario than the NN scenario as the burnt volume counted towards the aspatial optimized harvest level in the LP-based forest planning model. This caused salvage volume to replace green wood in the aspatial optimized harvest level, decreasing the rate at which the mature timber was being harvested from the land base. Burnt volume did not count towards the growing stock on the land base, so increasing the amount of harvestable volume on the land base decreased the constraint levels slightly, but other constraints in the model meant the aspatial optimized harvest level did not increase to a great degree.

The percentage of the aspatial optimized harvest level that Stanley allocated in this scenario was similar to that of the previous scenarios (Figure 3.8c). The AAC from this scenario was similar to the AAC from the NN scenario (Figure 3.9c). However, it was slightly higher due to the higher aspatial optimized harvest level in the NA scenario over the NN scenario. The spatially feasible aspatial optimized harvest levels were similar in the two scenarios but the final harvest level achievable in the two scenarios was very different. In the NN scenario salvage volume was additional to the AAC. This caused an increase in the harvest level of the NN scenario increasing harvest level to a higher level than the NA scenario. The benefits of counting salvage volume towards the IHL is an increased amount of mature green wood on the land base and a decrease proportion of the burnt area salvaged. The benefit of the decreased proportion of the burnt area salvaged is an increase in habitat for species that require post-fire areas. Also counting the salvage volume towards the aspatial optimized harvest level meant that less green wood was harvested in years with merchantable timber burnt. Also there would be a decline in the proportion of burnt timber that was salvaged, especially in high fire years. Reducing the green wood harvest in high fire years would cause a decline in the harvest rate of mature timber, increasing future timber available for harvest. This increase in future availability of mature timber would decrease the effect of future fires, which seem to have a larger effect on harvest level then fires in earlier periods.

The RA scenario had burnt areas immediately regenerating and the burnt volume counted towards the aspatial optimized harvest level. Of the four policy scenarios that were analyzed the RA scenario showed the least variability in aspatial optimized harvest level (Figure 3.7d). There were an increasing number of outliers in the later runs. The spatial allocation percentages in this scenario were similar to the all of the other scenarios (Figure 3.8d). The AACs showed the least variability of all of the policy scenarios analyzed (Figure 3.9d). The effect of adding regeneration to the NA scenario was the same as adding regeneration to the NN scenario, which was a decrease in the number of negative outliers. The cost of adding regeneration to the policy scenario was also the same, which was the financial cost of regenerating the fire areas. The effect of moving from the RN scenario to the RA scenario was the same as counting the salvage volume against the aspatial optimized harvest level in the NN to NA scenarios. There does not seem to be an additional effect of adding both policy changes to the NN scenario.

Stanley was only able to allocate between 80%-90% of the volume scheduled by the LP-based forest planning model, it was initially believed this created a large buffer against the effect of forest fires. Armstrong (2004) discussed the probability of sustainability and how by reducing the aspatial optimized harvest level there would be an increased probability that the harvest level would be sustainable when factor such as fire were incorporated. This theory was tested in using the RN scenario, by reducing the green up delay to zero years, this allowed approximately 100% of the aspatial optimized harvest level to be spatially allocated by Stanley (Figure 3.8f). Ten iterations were completed of this scenario. When the entire aspatial optimized harvest level was harvested in each run it can be seen that towards the end of the iterations there was a decrease in aspatial optimized harvest level. This was associated with the decrease in mature and over mature timber available for harvest from the land base. Therefore fires again showed a larger impact in later periods as mature timber became scarcer. This shows that the spatial allocation percentages protects future harvest but seems to have little effect until approximately 80 years from now. The reason that the reduced spatial allocation was not largely buffering the harvest was due to the fire modeling. Armstrong (2004) used a fire model that had equal burn probabilities for all for types. In this study the burn probability of the main species harvested were very low. Therefore the effects discussed by Armstrong (2004) would be more relevant if the main species in the study area had higher burn probabilities.

Overall this study showed how different fire policies would affect the long term harvest levels. This study shows that when analyzing the effects of fire policy the extremes are being managed for, as median fire years have very little effect on the land base. Adding regeneration to the historical fire policy stabilizes the harvest level over time but does not increase harvest from the land base to a noticeable degree. As regeneration is a very costly activity the stability in harvest may not be worth the expenditure, as only in extreme cases does fire cause a reduction in harvest level. The risk preference of an FMA holder may affect such a decision. If a company is willing to risk future declines in harvest levels they are able to save current regeneration costs. When discount rates are included the cost of regeneration becomes even larger when compared to the chance of a reduction in harvest level. However, if a future reduction in harvest would cause reduced mill efficiency due to a lack volume to process, and other volume is not available to purchase then it may be in the best interest of a company to regenerate the land base.

How the volume that is salvaged is managed changes the harvest from the land base a great deal. When the salvage volume is not counted against the aspatial optimized harvest level there is a surge of volume after fire. The slight increase in harvest level due to the salvage volume being counted towards the aspatial optimized harvest level is much smaller than the increase FMA holders receive when the salvage volume is not counted towards the aspatial optimized harvest level. When this is combined with the lower 'damaged' timber dues companies pay for salvaged volume, the benefits of not counting salvage volume towards the aspatial optimized harvest level is increased for FMA holders. However, the benefits associated with counting salvage volume against the

AAC may not be realized in the current fire policy scenario as government allows other tenure holders FMAs to salvage burnt timber not being salvaged by the affected tenure holder (Alberta Sustainable Resource Development, 2002).

Overall it can be seen that with a LP-based forest planning model and Stanley allocation procedures used here it may be in a companies best interest to let fires burn on the landscape if the volume does not count against the AAC. If company's are able to deal with fires on a case by case basis then it would be in their best interest to regenerate large fires that affect their aspatial optimized harvest level but not the smaller fires as they have little to no effect on the aspatial optimized harvest level.

The sequential re-planning scenarios used in this study was very computationally intensive. Each iteration took 3-4 hours to complete on a dual Xeon 3.2 GHz system with 1 gigabyte of RAM. It may have been ideal to run more iterations, or examine more scenarios, but there were already 420 iterations completed taking over 3 months of run time. This did not include pre-modeling, or initial development runs.

This study is specific to Alberta and other locations that have similar timber scheduling policies, and have excess mature and overmature wood on their operating land base. As without excess mature and overmature timber the effect of fire could be greater as if fire burns large amounts of harvestable mature timber it would cause a deficit of mature timber in early time periods. The main species that are harvested in this area have a very low flammability index. The study results may have varied if this study was conducted in an area where main species had a higher flammability index.

3.6 Conclusions

The manner in which post-fire land bases are dealt with affects the long run harvest levels from a land base. Regenerating post-fire land bases reduces the number of outliers during in extreme fire years. This reduction in outlier reduces the variability of future harvest level from the land base. When salvage volume is counted towards the AAC there is a lower harvest level in most cases than when the salvage volume is not counted against the AAC. It was seen that there is large spikes in harvest level that were associated with fires when the volume is not counted against the AAC. It was also seen in the modeling done for the study that the spatial allocation of the LP-based forest planning model may have buffered the forest area against declines in harvest level. The costs and benefits of each policy are difficult to measure and are choices that would vary depending on the risk preference of the decision maker and the desire of society.

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Chapter 4

Conclusion

There are numerous forest management agreement (FMA) holders in Alberta. These FMA holders have rights to harvest timber from designated areas within the province. Prior to harvesting timber companies must undertake an extensive planning process. One component of this planning process is an analysis of the timber supply on their designated harvest area (Alberta Sustainable Resource Development 1998). This timber supply analysis is commonly completed using linear programming (LP)-based forest planning models. These models maximize the harvest possible from their designated land base subject to user inputs and constraints. The complexity of these models varies depending on the chosen level of inputs, but even the simplest can be very complex.

Fires which often occur on the areas designated for harvest are not usually incorporated into LP-based forest planning models. Fires are stochastic events, making them difficult if not impossible to predict into the future. Fires that burn harvestable timber within FMA areas have an effect on the timber supply for that land base. This thesis presents studies that analyze the effects of forest fires on timber supply. Chapter 2 presents a method of approximating the cost of individual fires or land base removals using shadow prices. Chapter 3 presents a study showing the effect of fire salvage policy on long term harvest levels.

Chapter 2 presented a method of approximating the cost of land base removals using shadow prices. The cost, in this study, refers to the change to the objective function value. Two LP-based forest planning models were obtained from companies in Alberta along with spatial information for the corresponding areas. Major fires occurred in both of these study areas in the last decade (Alberta Sustainable Resource Development, 2004). The cost of these fires was first calculated using a traditional "remove and recalculate" approach. The results from the traditional method were then compared to area weighted shadow price approximations. It was shown that when, post-fire, the areas were removed from production, shadow prices accurately approximated the cost of these fires. This is consistent with the research of Armstrong and Cumming (2003), which showed shadow prices to accurately approximate the cost of simulated fire years. These shadow price approximations also accurately estimated the cost of land base removals, in the form of townships. However, chapter 2 also shows, in contradiction to the work of Armstrong and Cumming (2003), that shadow prices were unable to accurately approximate the cost of forest fires when the fire area was assumed to immediately regenerate.

Chapter 3 presented a study analyzing the effect of fire salvage policy on long term harvest levels from a land base in the boreal forest. Sequential re-planning simulations were used with simulated fires to analyze the effect of four different salvage policies. A LP-based forest planning model was created and optimized; subsequently Monte Carlo simulations were used to spatially allocate this optimized harvest, subject to green-up constraints. Fires were then incorporated onto the land base and the forest was aged. This planning process was repeated every 5 years for 20 periods, or 100 years. Two sets of constraints were analyzed. The first set of constraints regarded regeneration of the post-fire land base. The historical policy in Alberta allowed FMA holders to salvage burnt timber without regenerating the post-fire areas (Alberta Sustainable Resource Development, 2002). This land base would be reincorporated into the land base when the area was considered sufficiently restocked. More recently companies have regenerated post-fire areas and retained the areas in their LP-based forest planning models. Regenerating the post-fire area reduced the variability in harvest level from the land base.

The second set of policy options analyzed had to do with the management of the salvaged timber. Current policy does not count volume salvaged from post-fire areas towards an FMA holder's AAC. The other policy option analyzed had the volume salvaged count against the AAC. The results showed that counting salvage volume against the harvest level did not have a significant effect on the harvest level. The main effect of counting the salvage volume against the AAC was that there was not the high levels of salvage volume harvested post-fire. In high fire years this change caused a reduction in the proportion of burnt volume salvaged, as well as a decrease in the amount of green wood harvested. Though this is not necessarily consistent with what would happen, as other companies may salvage the volume not salvaged by the FMA holders.

Measuring and estimating the cost of forest fires in Alberta shows a number of interesting results. Firstly, it is possible to approximate the effect of forest fires using shadow prices. Secondly, fire salvage policy affect's the harvest level possible from a land base. In both of these studies it can be seen that managing forest fires, is largely managing for extreme events. Chapter 2 shows that large fires can reduce the harvest from a land base, but if the post-fire land base regenerates the effect of the fires on the harvest level is greatly reduced. Chapter 3 shows similar results as regenerating post-fire areas stabilizes harvest from a land base. It can be seen in Chapter 3 that fire normally burns very little area, however some years extreme fire events, which show up as outliers on a distribution of fire sizes occur. These extreme fire events are capable of changing the harvest level available from a land base.

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