Wildfire Management in the Southside Region of Canada's Montane Cordillera

A Systems Modelling Application on Firebreak Strategies

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Abstract

There is growing recognition of the importance of preserving Canada's forests. Canada's 348 million hectares of forest land cover 35% of its land area, representing 9% of the world's forests and 24% of the world's boreal forests. As a renewable resource, forests offer significant environmental, economic and recreational benefits and innumerable services contributing to the quality of life.

Canada has recently entered an era of increased frequency and severity of natural disasters. Ecosystems and communities especially in western Canada have recently undergone a trend of increasing pressures from natural disturbances. These disturbances include wildfires associated with increased fuel load levels from past fire suppression regimes and a widely spread infestation of the mountain pine beetle in addition to changes in weather patterns. Wildfire activity has reached extreme levels in many of the recent years.

This thesis profiles an area of western Canada within the Montane Cordillera covering the Nechako Lakes Electoral District in central British Columbia and assesses its vulnerability to the specific hazard of wildfires caused by natural and man-made sources. The objectives of this research are to review, simulate and assess the impact of various fuel management strategies in a sub-section of the Nechako Lakes Electoral District called the Southside. Values at risk include private property and old growth forest in respectively timber supply areas, provincial parks, woodlots and community forests.

Simulation results show that firebreaks are effective in significantly reducing the area burned in different parts of the landscape. The performance of different strategies shows large variation. Although this has not been investigated further, such variation has likely been caused by topographic aspects and the positioning of firebreaks in the landscape in relation to climatic parameters. These results can therefore not be extrapolated beyond the simulated area, but do give an indication of the performance variation that may be expected when similar firebreaks are applied elsewhere. The results also show that model performance of all firebreak strategies is heavily and fairly consistently influenced by weather stream parameters. Sensitivity analyses of weather stream parameters show that although the reduction in total area burned varies, the ranking between strategies in their overall performance is consistent regardless of the weather pattern. Combined dry, warm and windy weather conditions lead to a 3.44-fold increase in total area burned as compared to the scenario with average weather conditions. In favourable weather conditions represented by wet, cold and nearly windless conditions, the model shows an 85% reduction in total burned area as compared to the average scenario. These results illustrate the significant impact of uncontrollable variables on the overall result.

Keywords: geographic information systems, geo-statistics, fuel management strategies, simulation modelling, spatial data modelling, wildfire management

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List of Terms and Acronyms

The following section itemizes common abbreviations found in the writing of this document.

AAC	Annually Allowable Cut
AOI	Area of Interest
ArcGIS	GIS software working with maps and geographic information.
ArcInfo	ESRI Geographic Information System Software
ASCII	American Standard Code for Information Interchange
BASE	Baseline strategy
BC	British Columbia
BP	Burn Probability
BMTS	Biodiversity, Mining and Tourism Area (Crown land)
CFFDRS	Canadian Forest Fire Danger Rating System
CNFDB	The Canadian National Fire Database - Fire Point and Polygon Data is a collection of forest fire locations and fire perimeters as provided by Canadian fire management agencies including provinces, territories, and Parks Canada.
COM	Common Object Model
COMF	Community Forest strategy
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
FBP	Fire Behaviour Prediction
FEMA	Federal Emergency Management Agency
FREP	Forest and Range Evaluation Program, led by led by the B.C. Ministry of Forests, Lands and Natural Resource Operations in collaboration with the Ministry of Environment.
FSI	Fire Susceptibility Index
MFLNRO	Ministry of Forests, Lands and Natural Resource Operations
FPI	Fire Potential Index: a moisture-based vegetation flammability indicator. It is a function of current living vegetation greenness as a proportion of maximum greenness, and current 10-h dead fuel moisture as a proportion of the moisture of extinction. The FPI is calculated for different areas and time periods by the Wildland Fire Assessment System for the continental U.S.
FWI	Fire Weather Index
GIS	Geographic Information System
PARK	Provincial Parks strategy
PRIV	Private Property strategy
SEDA	Southside Economic Development Association
SDM	Spatial Data Modeller
TFL	Tree Farm Licence
TSA	Timber Supply Area
TSA1	Timber Supply Area strategy
TRIM	Trimline Mapping from Multispectral Landsat
TM	Thematic Mapper
UREP	Use, Recreation and Enjoyment of the Public
VBA	Visual Basic for Applications
WLOT	Woodlots strategy

1. Introduction

1.1 History, background and motivation

There is growing recognition of the importance of preserving Canada's forests. Canada has 348 million hectares of forested land, 94% of which is publicly owned and 6% privately owned. Canadian forests cover 35% of its land area, representing 9% of the world's forests and 24% of the world's boreal forests. As a renewable resource, forests offer significant environmental, economic and recreational benefits and innumerable services contributing to the quality of life. In 2014, Canada exported $31 billion in forest products to nearly every nation on the planet (Lee, 2004; Natural Resources Canada, 2015a).

Canada has recently entered an era of increased frequency and severity of natural disasters (The Pembina Institute and Canada's Boreal Initiative, 2005). Ecosystems and communities especially in western Canada have recently undergone a trend of increasing pressures from natural disturbances. These disturbances include wildfires associated with increased fuel load levels from past fire suppression regimes and a widely spread infestation of the mountain pine beetle (*Dendroctonus ponderosae*) in addition to changes in weather patterns. Wildfire activity has reached extreme levels in many of the recent years (Natural Resources Canada, 2016cd). The largest wildfire evacuation in Albertan history up to now is also the most recent one and the costliest natural disaster in Canadian history. In May 2016, an area of over 0.6 million hectares destroyed parts of Fort McMurray and surrounding communities in northern Alberta, instantly forcing a temporary shutdown of oil sands operations and forcing the evacuation of over 90000 people. The impact of this wildfire is at an unprecedented level above and beyond the 2011 Slave Lake wildfire (Wikipedia, 2011, 2016). This trend raises questions about underlying causes, which may not be limited to global warming and may possibly include El Niño effects (Globe and Mail, 2016).

Throughout history, natural disturbances have played an essential role in preserving and shaping biodiversity in BC's ecosystem (Natural Resources Canada, 2015a). The effect of fire suppression practices along with logging and forest monoculture since the arrival of European settlers has led to densification of vegetation, making it more vulnerable to the occurrence of stand-replacing wildfires (Gedalof, 2016). Another factor contributing to the frequency and intensity of wildfires is the changing climate. While the trend is clear and well accepted, there is uncertainty about the rate and duration of change, in part because these factors depend on future emissions strategies. On average, wildfire threatens about 20 communities and 70,000 people annually in Canada, and fire management costs Canada about $700 million a year. Both the area burned and costs are expected to rise as a result of climate change. In British Columbia, fire records show that the wildfire season has been increasing in length by one to two days a year since at least 1980 (BCMOFR, 2009).

In recent years, British Columbia has been subjected to increased costs and damages associated with wildfire activity, with large areas burned in 2003, 2010, 2014, 2015 and 2016. The 2003 wildfire season in British Columbia for example, was particularly dramatic. More than 2500 wildfires caused unprecedented damage to homes, business and public infrastructure. As a result of these so-called firestorms, three pilots lost their lives, 334 homes and businesses were destroyed and 4500 people were evacuated from their homes. The total cost of these fires was estimated at $ 700 million (Filmon, 2004; Richardson, 2010). Table 1.1 shows the number and percentage of people and lightning-caused fires in British Columbia between 2004 and 2015. In this period the province was subject to 1817 fires of which 700 (38.5%) were caused by human activity and 1117 (61.5%) by lightning (BCMOFR, 2016). The average cost of firefighting from 2004 to 2015 was CAN$ 1125.20 per hectare.

Although this short-term upward trend in area burned is noticed across Canada, the pattern when reviewed over a larger time period shows high variability but not necessarily an upward trend. Figure 1.1 shows the extent of area burned in Canada due to wildfires from 1970 to 2014 (Natural Resources Canada, 2016bc). Although the short-term trend in total area burned annually is upwards, the long-term trend in BC when measured between 1950 and 2012 does not illustrate any upward trend. Nevertheless, fire seasons have shown increased variability and length, with higher activity before and after the peak fire months of June, July and August (MFLNRO, 2014; Natural Resources Canada, 2016b).

In order to better understand the complexity and dynamics of these trends, there is a growing need to study ways and means of adaptation to and reduction of the threats to resources and communities due to the increased risk of wildfires in western Canada. This thesis addresses firebreak management strategies for the reduction of wildfire risks.

1.2 Research questions and objectives

The main focus of this research is to improve existing firebreak strategies in dealing with wildfire risk by communities in the Nechako Lakes District, as described in research question 3 below. This requires a preliminary and inherent understanding of existing vulnerabilities and fuel management strategies in the Nadina Forest District, as reflected by research questions 1 and 2 respectively.

The **research questions** are:
1. What are the vulnerabilities of remote rural communities in the Nechako Lakes Electoral District in BC to wildfires?
2. Which wildfire fuel management strategies are currently used in protecting these communities from wildfires?
3. How can firebreaks be applied in protecting remote rural communities within this area?

The **research objectives** corresponding to the research questions above, are as follows:
1. Describe the characteristics and community profiles of the Nechako Lakes Electoral District with reference to their economic, environmental, social and cultural components, with emphasis on the Nadina Forest District.
2. Review wildfire fuel management strategies with particular attention to the Nadina Forest District; review software applications in geographic information systems used for wildfire simulations.
3. Analyze geographical data to quantify the probability density function of hazards caused by wildfires; perform simulations to assess the impact of implementing strategic firebreaks in a sub-section of the Nechako Lakes Electoral District called the Southside; on the basis of the simulation results, provide tools and strategy recommendations for protecting values at risk for remote rural communities.

Three distinct scope areas were defined for this study, all of which are entirely located within the Montane Cordillera Ecozone as described in section 2.4.1. Historic wildfire data were collected from the Nechako Lakes Electoral District (section 2.4.2). The Nadina Forest District as a sub-set of the Nechako Lakes Electoral District is the specific area of study in terms of the existing and potential wildfire fuel management strategies to be applied (section 2.4.3). The Southside region was chosen for simulation purposes. The following paragraph further elaborates on the rationale for choosing these three distinct scope areas.

The Nechako Lakes District was chosen as scope area for data collection in order to cover a sufficiently large area enabling the collection of sufficient information to warrant reliable estimates of historic averages and trends. The characteristics of this area are described in section 2.4.2. The Nadina Forest District described in section 2.4.3 was scoped for strategy and policy analyses as it lies entirely within the Nechako Lakes Electoral District and is therefore a tangible entity from which reports on forestry policies and macro-economic data for strategy assessment are available in the literature. The Southside area described in section 2.4.4 and consisting of Timber Supply Area Blocks E and F within the Nadina Forest District, is the area where the developed wildfire simulations are applied in this research. It was selected as a sub-set of the Nadina Forest District for two reasons. Firstly, its relatively small size enabled simulations yielding reliable output to be performed, requiring cell resolutions between 30 and 100 metres (Perrakis, 2015; Strimbu, 2015; Tymstra et al, 2010). Secondly, it was the area most familiar to the author in terms of topography, which was seen as a potential advantage in being able to interpret simulation results.

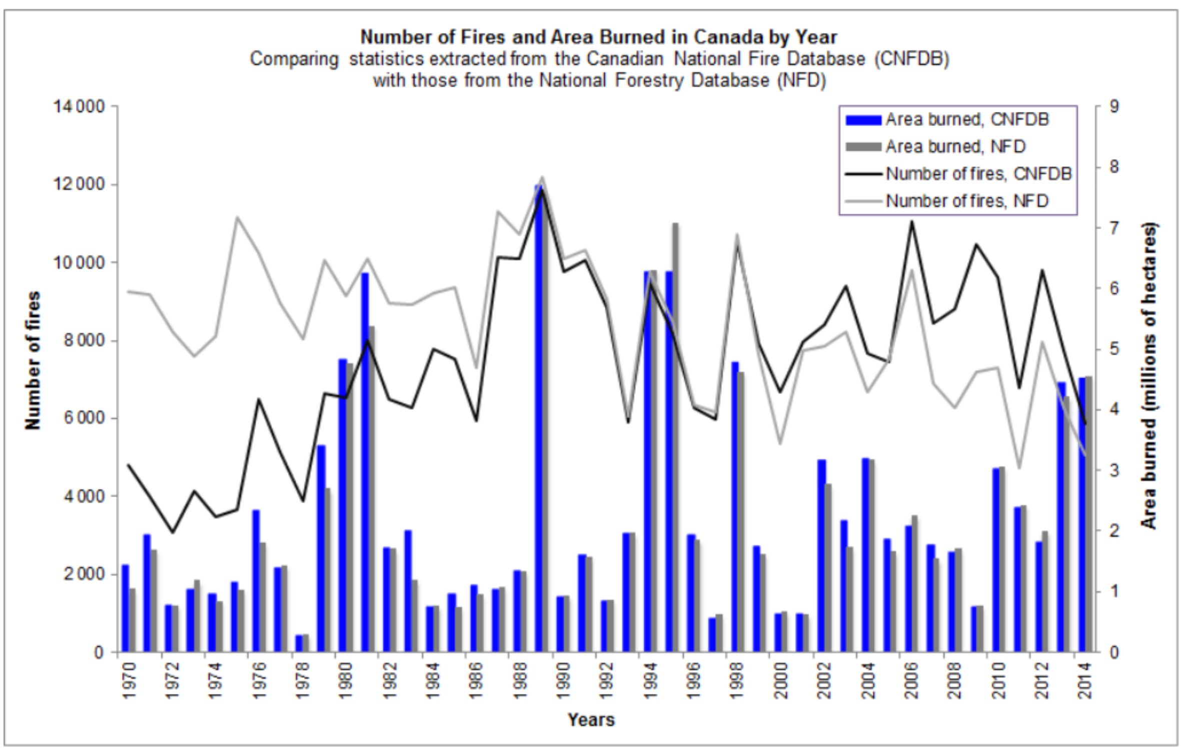


Figure 1.1 Area burned in Canada between 1970 and 2014
Source: Natural Resources Canada, 2016b

Table 1.1 Wildfires in BC from 2004-2015 by cause

Year	Total Fires	Total Hectares	Total Cost (millions)	Average Hectares per Fire	People-Caused		Lightning-Caused		Firefighting cost ($) per ha
					Fires	%	Fires	%	
2015	1858	280,484	$277.0	204.9	617	33.2%	1237	66.6%	987.58
2014	1481	369,168	$297.9	249.3	664	44.8%	817	55.2%	806.95
2013	1861	18,298	$122.2	9.8	564	30.3%	1297	69.7%	6678.33
2012	1649	102,122	$133.6	61.9	708	42.9%	941	57.1%	1308.24
2011	653	12,604	$53.5	19.3	444	68%	209	32%	4244.68
2010	1672	337,149	$212.2	201.6	680	40.7%	992	59.3%	629.40
2009	3064	247,419	$382.1	80.8	881	28.8%	2183	71.2%	1544.34
2008	2023	13,240	$82.1	6.5	848	41.9%	1175	58.1%	6200.91
2007	1606	29,440	$98.8	18.3	687	42.8%	919	57.2%	3355.98
2006	2570	139,265	$159.0	54.2	1034	40.2%	1536	59.8%	1141.71
2005	976	34,588	$47.2	35.4	591	60.6%	385	39.4%	1364.64
2004	2394	220,518	$164.6	92.1	681	28.4%	1713	71.6%	746.42
Average	**1817**	**150358**	**$169.18**	**82.74**	**700**	**38.5%**	**1117**	**61.5%**	**1125.20**

Source: BCMOFR, 2016

1.3 Thesis Outline

The topics in this thesis have been arranged as follows:

Chapter 1. Introduction (this chapter).

- Provides background information on wildfire management in British Columbia. Motivation for the undertaking of this study.

Chapter 2. Literature Review

- Describes characteristics and community profiles of the Nechako Lakes Electoral District, BC with reference to economic, environmental, social and cultural components.
- Reviews actual and/or historical wildfire fuel management strategies in the Nechako Lakes Electoral District.
- Analyzes historical data to quantify the probability density function of wildfires, to assess the vulnerability of the Southside community in British Columbia.
- Reviews software applications in geographic information systems and geo-statistics and their applications in the Nadina Forest District.

Chapter 3. Methodology

- Outlines the research methodology and application of software tools to address the research questions and to carry out the wildfire simulations.

Chapter 4. Analysis and Results

- Establishes a Baseline Case, validated by historical data from the Nechako Lakes Electoral District.
- Simulates, compares and evaluates firebreak strategies to assess their impact on total area burned.
- Develops Sensitivity analysis, performance comparison and ranking

Chapter 5. Discussion

- Discusses the research outcomes, data availability and decision support. Develops Policy Implications for Adaptive Management.

Chapter 6. Conclusions and recommendations

- Provides a summary of conclusions, research limitation of the current work, along with policy recommendations for employing resources for risk mitigation.

Finally, this thesis also contains detailed appendices for the presentation of data, the development of the software methodology, and the output of the simulation analysis model results.

2. Literature Review

This chapter is divided into five sections. Section 2.1 provides information on Canada's ecozones and forest regions. Section 2.2 deals with resource planning in forestry, followed by section 2.3 covering the history and trends in wildfire fuel management strategies. Section 2.4 provides information on the scope areas related to geographic, demographic and socio-economic indicators. Section 2.5 provides a review of software applications used by Canadian forestry scientists for geographic analysis and modelling. A summary of the reviewed literature critical to this research is provided in section 2.6.

2.1 Canada's Ecozones and Forest Regions

Forests in Canada are classified according to three main types of classification: **ecozones, forest regions and plant hardiness zones**. Together these classifications provide a science-based foundation for forest management decision-making at the national level (Natural Resources Canada, 2016a). The National Forest Inventory, a collaborative effort between the federal, provincial and territorial governments, compiles detailed information for each of Canada's forested ecozones. The provinces and territories collect data using consistent standards and procedures. The Canadian Forest Service maintains the database and leads data analysis and reporting. The provinces and territories have also developed their own ecological and land classification systems to further classify the characteristics of their forest landscapes.

An **ecozone** is defined as an area of the earth's surface representative of a large and generalized unit characterized by interactive and adjusting abiotic and biotic factors (Wiken, 1986ab). In addition to ecozones, smaller portions can be defined within ecozones, including ecoregions and ecodistricts (Ironside 1991). An **ecoregion** is a part of an ecozone characterized by distinctive regional ecological factors, including climatic, physiography, vegetation, soil, water, fauna, and land use. An **ecodistrict** is a part of an ecoregion characterized by distinctive assemblages of relief, geology, landforms and soils, vegetation, water, fauna, and land use. Canada's landmass was first subdivided into 15 terrestrial ecozones to meet reporting requirements of the first State of the Environment Report for Canada (Ecological Stratification Working Group, 1995; Marshall and Schut, 1999; Natural Resources Canada, 2016b). A map of Canada's terrestrial ecozones is given in Figure 2.1.

A **forest region** is a geographic zone with a vegetation cover that is fairly uniform in terms of dominant species and stand types. In Canada, the system that has long been used to classify forest land divides the territory into regions. Unlike ecozones, a forest region classification does not incorporate all of the environmental variables, but relies mainly on the nature of the vegetation or forest composition to classify the regions (Natural Resources Canada, 2016b). A map of Canada's forest regions is given in Figure 2.2.

A **plant hardiness zone** represents an area where various types of trees, shrubs and flowers will most likely survive based on the average climatic conditions. The original hardiness zones were developed in the early 1960s. Since then Canada's climate has changed and climate mapping techniques have improved, allowing Canadian Forest Service scientists to update and remap the plant hardiness zones while using more recent data and by incorporating additional variables into the original equations (McKenney et al, 2001; Natural Resources Canada, 2016b).

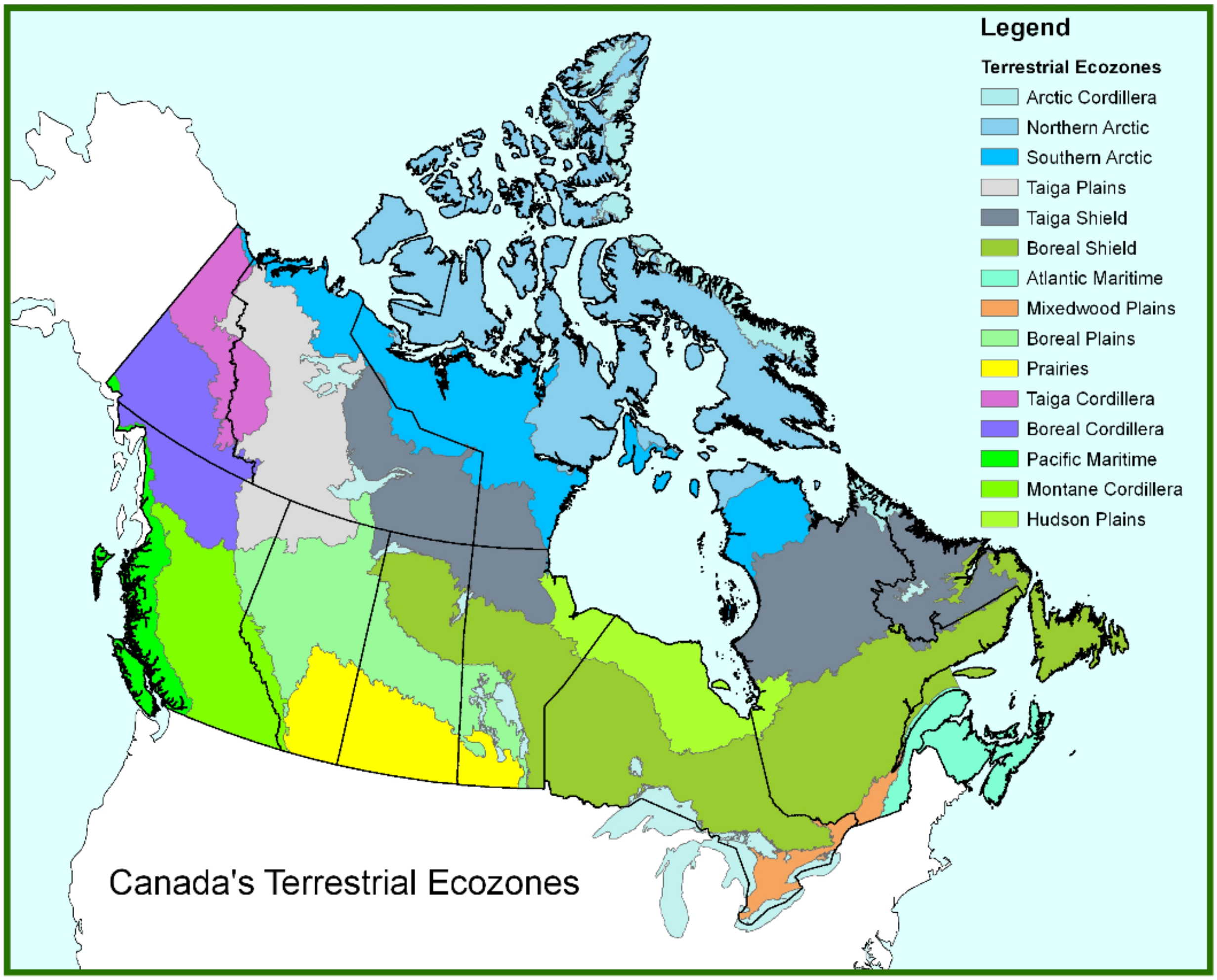


Figure 2.1 Canada's Terrestrial Ecozones
Sources: Ecological Stratification Working Group, 1995; Natural Resources Canada, 2016b.

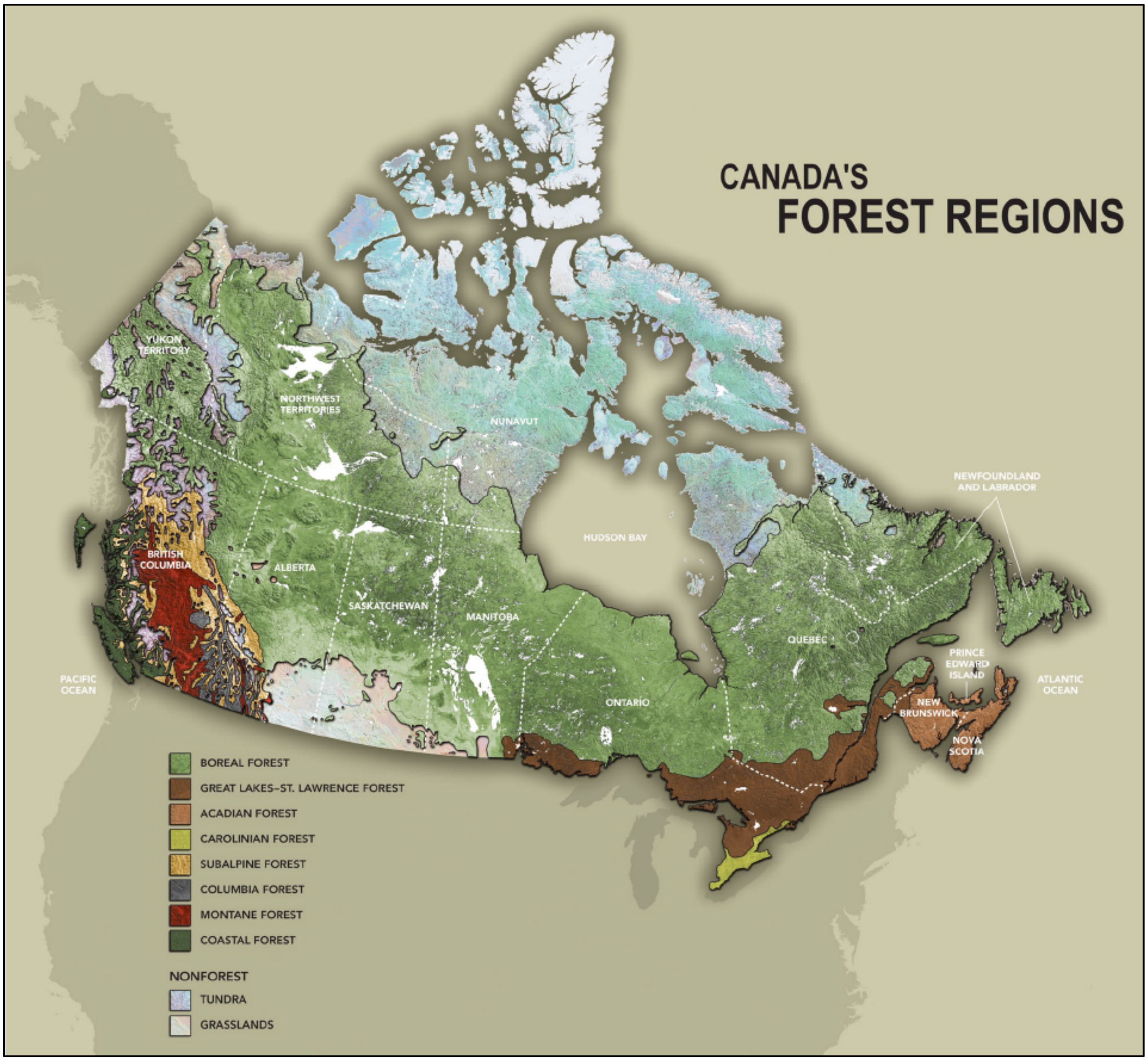


Figure 2.2 Canada's Forest Regions
Source: Natural Resources Canada, 2016b.

2.2 Resource Planning in forestry

In business, military and government planning, a critical distinction is often made between **strategic, tactical and operational** resource planning. Strategic planning involves the long-term vision and mission of an entity, whereas tactical planning deals with the actual steps needed to achieve that vision. Operational planning regulates the day-to-day output relative to schedules, specifications, and costs (Mintzberg and Quinn, 1996; Boundless, 2014).

In forestry management, strategic planning is conducted to facilitate decisions on forestry within legislative and policy constraints (Martell et al, 1998; Gunn, 1991; Gunn, 2004; Gunn, 2007). The time window for strategic planning in forestry is partially dependent on the rotational cycle of the forest.

Strategic forest planning is generally concerned with macro-level investment decisions such as mill capacity, spraying and infrastructure (Hirsch and Fuglem, 2006; Moll, 1991; Moll, 1992). Planning windows of up to 100 years have been commonly used (Andersson, 2005).

In tactical planning, the purpose is to schedule harvest operations to specific areas and on a finer time scale than for strategic planning. Tactical planning occurs at the stand level with the coordination of forestry activities such as cutting, thinning and planting. The tactical planning model enables measurement of the impact of local investment decisions associated with these activities (Martell et al., 1998; Moll, 1991; Weintraub et al, 1986).

Operational forest planning is focused on improving methods for planning, organizing and executing forest plans, as well as the enhancement of supply chain efficiency and improving competitiveness (USDA, 1978).

At the tactical and operational levels, a multitude of scientific endeavours has been undertaken using remote sensing techniques to compute ignition probabilities and compare fire risk across ecoregions (Dasgupta et al., 2005). A so-called Fire Susceptibility Index (FSI) was demonstrated to be a good estimator of fire risk, when using fuel moisture and fuel temperature as inputs and validating the results with the Fire Potential Index (FPI). The FSI has also been modelled and linked to pre-emptive measures enabling land managers to reduce the likelihood that an area will be burned by wildfire (Beverly et al., 2009). Their research demonstrates the complexity of factors determining fire susceptibility. Modelled fire susceptibility was highly affected by fuel composition and fuel arrangement as well as by topography. Prioritizing and evaluating strategic wildfire fuel management strategies requires an understanding of variations in weather and local topography. Their simulations demonstrated the effective use of prescribed fire treatments to reduce forest fire susceptibility.

A qualitative review of the community impacts of wildfire was undertaken by Krishnaswamy et al (2011). Human impacts were categorized between social, health and safety, social or cultural and between short-term and long-term. When dividing planning into distinct levels, discrepancies between the alignment of strategic and tactical plans may occur. In decision support models, solutions at one level may be inconsistent with the results of another level. When moving from the strategic plan to the tactical plan, three sources of inconsistencies are often present; discrepancies that are spatial, temporal or due to different levels of constraint. Depending on the cause, various approaches can be taken to deal with such discrepancies (Andersson, 2005).

A responsive, evolving natural resource system requires adaptive management strategies that influence, and are influenced by, systems dynamics. Mathematical modelling methodologies have been applied to deal with the complexities of forest management (Moll, 1991; Moll, 1992). In order to provide accuracy and insight, decision support models and adaptive management strategies in response to wildfires must be considered at the respective levels of forest management and planning.

2.3 Wildfire fuel management strategies

2.3.1 Goal

In order to facilitate planning, resource management in fire-prone ecosystems requires an understanding of wildfire behaviour and a viable approach to evaluating burn probability. Management strategies have been described in a number of studies (Keane et al, 2014; Parisien et al., 2005).

Wildfire plays a vital role in the conservation of biodiversity of various ecosystems. Traditional forest management practices by First Nations allowed for periodic and consistent replacement rates of older stands of trees, creating a complex and diversified landscape in terms of wildlife habitat, vegetation and age. European settlers introduced rigorous fire suppression techniques, thereby decimating the occurrence and impact of forest fires, thus causing dramatic build-up of forest fuels over time (Forest Practices Board, 2015b).

Wildfire behaviour is defined as "the manner in which fuel ignites, flame develops and fire spreads and exhibits other related phenomena as determined by the interaction of fuel, weather and topography" (Merrill and Alexander, 1987). This concept is known as the fire behaviour triangle presented in Figure 2.3.

The overall goal of wildfire fuel management is to change the fuel complex in order to modify wildfire ignitions and fire behaviour to facilitate suppression efforts and reduce wildfire impacts (Hirsch et al., 2004). The key areas of intervention using wildfire fuel management are landscapes that are composed of a mosaic of alternate stable states and that connect or fragment areas in the same alternate state, such as boreal forests that are often a mosaic of varying patches of stand types and ages (Finney, 1999; Finney and Cohen, 2003; Peterson, 2002).

Figure 2.3 Fire Behaviour Triangle
Source: Alberta Government, 2016

2.3.2 Wildfire fuel management methods

The following wildfire fuel management methods have been applied or considered in practice. These methods can be applied within the constraints of forest cover requirements, designated wildlife habitat areas and protected areas such as national and provincial parks (Daust, 2011; BCMOFR, 2006/2007/2008).

1. Control human access during high hazard times.
2. Reduce post-harvest fuels.
3. Create natural firebreaks to increase chance of future fire containment.
4. Provide more and better fire-suppression equipment on site.
5. Improve access for fire suppression.
6. Structural enhancement of defensible spaces.
7. Prescribed burning.
8. Change harvesting regimes for trees and vegetation.
9. Use herbivores for wildfire fuel management.
10. Enhance biodiversity.
11. Improve forest health.
12. Provision of insurance policies (public or governmental).

Wildfire Fuel Management can be categorized as fuel reduction, fuel conversion, fuel isolation and fragmentation.

Fuel reduction consists of reducing fuel loads by using periodic prescribed burns or thinning practices. **Fuel conversion** entails replacing highly flammable coniferous fuels with less flammable deciduous fuel. This can be done through harvesting and/or prescribed burning followed by planting deciduous species. **Fuel isolation** and **fuel fragmentation** aim to fragment fuels through the use of roads, cut blocks and firebreaks, thereby reducing the vertical and horizontal continuity of flammable fuels (Agee & Skinner, 2005; Fernandes & Botelho, 2003; Partners in Protection, 2003).

Table 2.1 provides a categorization of wildfire fuel management strategies addressing wildfire hazards. These are described in the following paragraphs.

Table 2.1 Wildfire fuel management strategy categorization

Wildfire Fuel Management Strategy ↓	**Fuel Management Category**		
	Fuel Ignition	**Fuel Reduction, conversion, isolation, fragmentation.**	**Fuel Suppression**
Human access control	■		
Landscape level treatments: • Prescribed burning • Mechanical thinning, preventive logging, increased harvesting • Firebreaks • Random dispersed fuel treatments • Change in land use		■	
Increase firefighting capability and Early detection capability			■

References: Martell, 1982; Pyne, 1984

2.3.2.1 Prescribed burning

Prescribed burning involves the deliberate application of fire in fuels, under predetermined conditions in order to reduce fuel loads. Prescribed burns are effective in reducing fine fuels, large woody fuels, rotten material, shrubs and other live surface fuels, thus drastically reducing fuel loads of treated areas, thereby reducing flammable continuity of fuels and effectively reducing fire behaviour. If implemented randomly across the landscape in highly flammable fuels to mimic smaller fire events, prescribed burning might help reduce the size of extreme wildfire events. Treatments are likely to be a good first step in assisting in the long-term reintroduction of ecological disturbances. A combination of prescribed burning and mechanical thinning has proven to be effective.

Prescribed burning faces a number of challenges. It is less precise in comparison to mechanical thinning (described below). Also, the potential of escaped fires can make prescribed burning a politically sensitive decision for planners. Treatments might not be sufficient on their own to achieve structural goals of forest restoration. More systematic research is required to expand knowledge and understanding of prescribed burning, based on additional experimental findings in systems with different fuels composition and structure (Agee & Skinner, 2005; Fernandes & Botelho, 2003; Graham et al., 2004; Hirsch et al., 2004; Finney et al., 2005).

2.3.2.2 Mechanical thinning, preventive logging and increased harvesting

Mechanical thinning involves methods to reduce vertical and horizontal fuel continuity, thus reducing ladder fuels and the fire hazard for 10 or more years. Its benefits are several. The resulting reduction in fire behaviour from thinning treatments usually outweighs increases in fire weather factors, when thinning is followed by adequate treatment of surface fuels through prescribed burning. Prescribed burning and thinning practices as part of fuel treatment prescriptions can benefit other management objectives such as producing forage for wildlife, producing timber products, creating disease and insect resistant stands as well as slowing down fire behaviour, thus reducing area burned. A combination of prescribed burning and mechanical thinning has proven to be effective.

Mechanical thinning also has a number of drawbacks. It can increase the surface fuel load causing increased wildfire intensities. Mechanical thinning can create gaps and increase the amount of solar radiation that reaches the surface floor, thus increasing surface temperature, creating drier conditions suitable for ignition. These gaps allow for increased surface winds to carry an ignition. It is difficult to model forest thinning (fuel reduction) in comparison to fuel isolation and fuel conversion. The assumption that forest thinning will help restore healthy forests is potentially flawed as it can locally have the opposite effect (Agee & Skinner, 2005; Graham et al., 2004; Loehle, 2004, Fiedler & Keegan, 2003; Finney, 2001; Omi & Martinson, 2004; Weatherspoon & Skinner, 1996; Stephens, 1998; Kauffman, 2004).

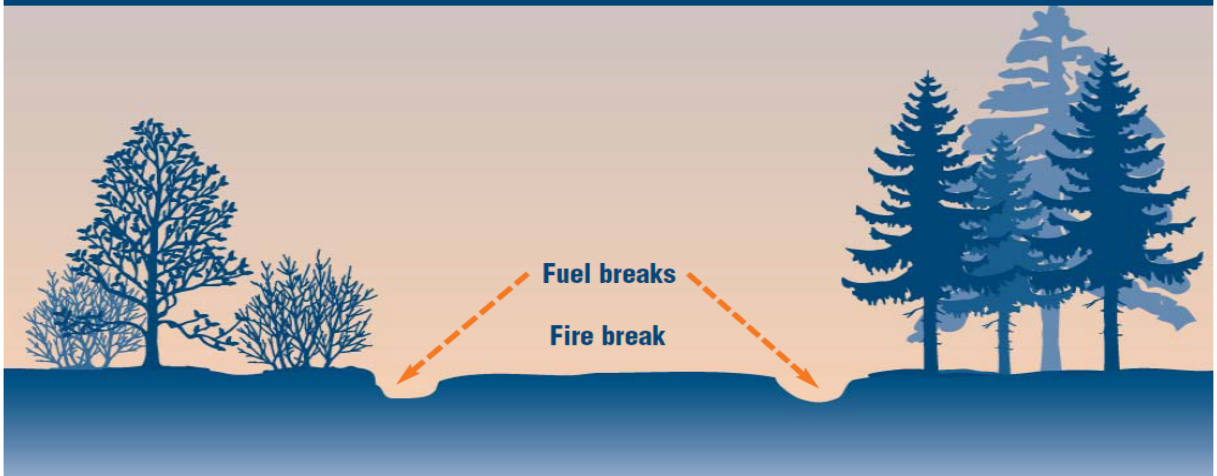
2.3.2.3 Strategic Firebreaks

A firebreak is defined as a barrier to fire spread built by clearing or significantly thinning fuels on a strip of strategically located land. Fuelbreaks are trenches dug down to mineral soil that stop fire spread. The community fireguard incorporates both firebreaks and fuelbreaks. These entities are illustrated in Figure 2.4 (Partners in Protection, 2003).

The placement of strategic firebreaks can reinforce existing defensible locations used to stop fire spread. This method is relatively inexpensive in comparison to random treatments. It is also beneficial in slowing or stopping fire spread containing the fire perimeter. Another advantage of this method is that it increases accessibility to an area.

One of the challenges with strategic firebreaks is that its effectiveness of changing fire behaviour from within the fire is limited. If the containment line is breached, the fire will continue to grow in size and intensity, requiring continual direct attack measures. It is also not effective in limiting the spread of so-called crown fires, which are fires jumping from crown to crown ahead of the ground fire. Strategic firebreaks require systematic application to be successful at limiting landscape level fire size. It has been found difficult to determine the percentage of the landscape that requires fuel treatment and the placement of these treatments to most effectively reduce wildfire hazards (Finney, 2001; Finney and Cohen, 2003; Graham et al., 2004; Loehle, 2004; Hirsch et al., 2004).

What is a Community Fireguard?

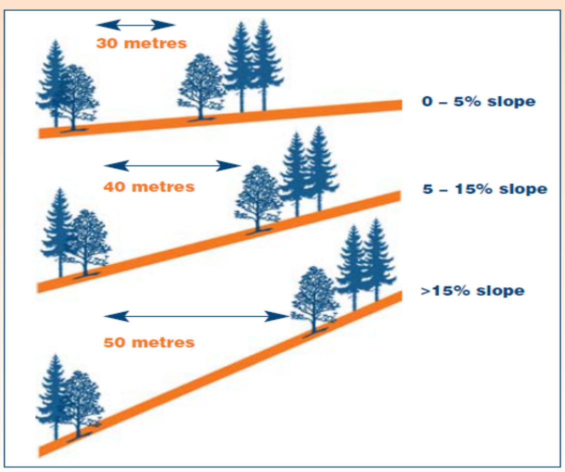


The community fireguard incorporates both fire breaks and fuel breaks. Fire breaks are barriers to fire spread built by clearing or significantly thinning fuels on a strip of strategically located land. Fuel breaks are trenches dug down to mineral soil that stop surface fire spread.

Fire break Guidelines

1. The width of the fire break will vary with the slope.

Slope/Width of Fire break	
0 - 5 %	30 m
5 - 15 %	40 m
> 15 %	50 m



2. Widen the fire break where gullies and terrain variations increase the slope.
3. Remove, reduce, or convert vegetation within the entire width of the fire break to a less aggressive standard for at least 5 metres on both sides of the fire break. Increase this 5-metre zone to 10 metres or beyond where high fire behavior levels are anticipated. Vegetation management should meet the same minimum standards as are used for the Priority zones 1 and 2.
4. Build a fuel break on both sides of the firebreak. The fuel break should be one metre wide, dug down to mineral soil and water-barred where needed. (Water bars are channels built across the exposed soil of the fuelbreak perpendicular to the slope—channelling runoff water before it can rush down the hill causing excessive erosion or gullying.)

Figure 2.4 Definitions and guidelines for firebreaks
Source: Partners in Protection, 2003

2.3.2.4 Random Fuel Treatments

Random fuel treatments involve applying random disperse fuel treatments throughout a landscape. In regions where long-distance spotting is common with extreme events, random disperse fuel treatments may be more effective at limiting fire growth than strategic and networked treatments, by reducing ignition and growth potential. A critical fraction of fuel fragmentation is needed to create a successful landscape-scale firebreak between wild-land areas and development zones. This means that random fuel treatments are needed throughout the majority of the forest in order to be successful. Similar to strategic firebreaks, it has been found difficult to determine the percentage of the landscape that requires fuel treatment and the placement of these treatments to most effectively reduce wildfire hazards (Agee & Skinner, 2005; Fernandes & Botelho, 2003).

2.3.2.5 Change in Land Use

Restrictive land-use policies can significantly curb the potential damage of rural wildfires (Headwaters Economics, 2016; Paveglio et al., 2013). An application in Canada is the FireSmart Program as part of the Strategic Wildfire Prevention Initiative (Forest Practices Board, 2015b; Partners in Protection, 2003).

2.4 Study area characteristics

This section provides metadata on the study areas in scope, covering geographic, demographic and socio-economic indicators.

Figure 2.5 displays the three distinct scope areas for this study, all of which are entirely located within the Montane Cordillera Ecozone as described in section 2.4.1. Historic wildfire data were collected from the Nechako Lakes Electoral District. The Nadina Forest District as a sub-set of the Nechako Lakes Electoral District, is the specific area of study in terms of the existing and potential wildfire fuel management strategies to be applied. The Southside region was chosen for simulation purposes. The following paragraph further elaborates on the rationale for choosing these three distinct scope areas.

The Nechako Lakes District was chosen as scope area for data collection in order to cover a sufficiently large area enabling the collection of sufficient information to warrant reliable estimates of historic averages and trends. The characteristics of this area are described in section 2.4.2. The Nadina Forest District described in section 2.4.3 was scoped for strategy and policy analyses as it lies entirely within the Nechako Lakes Electoral District and is therefore a tangible entity from which reports on forestry policies and macro-economic data for strategy assessment are available in the literature. The Southside area described in section 2.4.4 and consisting of Timber Supply Area Blocks E and F within the Nadina Forest District, is the area where the developed wildfire simulations are applied in this research. It was selected as a sub-set of the Nadina Forest District for two reasons. Firstly, its relatively small size enabled simulations yielding reliable output to be performed, requiring cell resolutions between 30 and 100 metres (Perrakis, 2015; Strimbu, 2015; Tymstra et al, 2010). Secondly, it was the area most familiar to the author in terms of topography, which was seen as an advantage in being able to interpret simulation results.

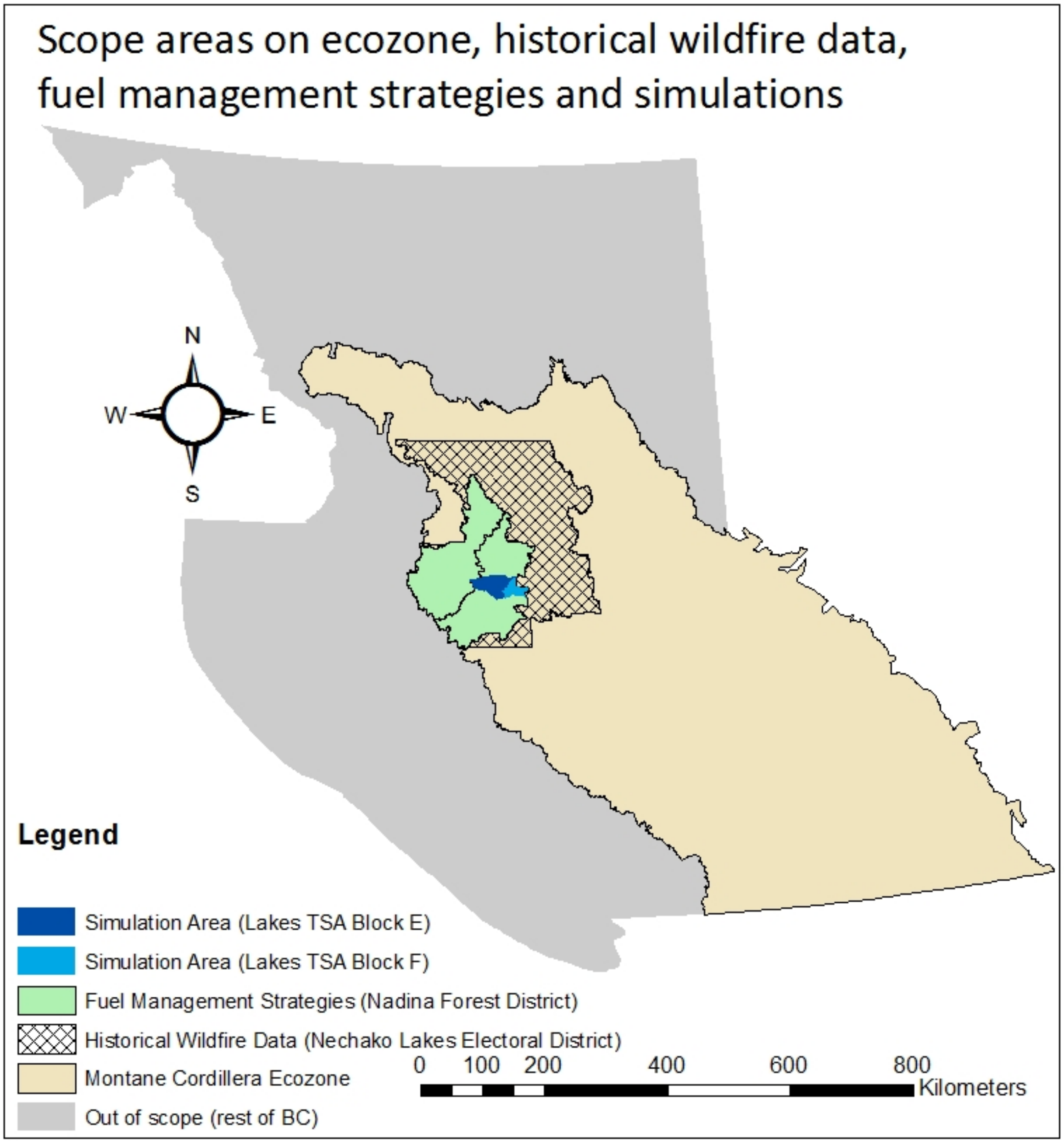


Figure 2.5 Mapping of scope areas

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

2.4.1 Montane Cordillera Ecozone

The Montane Cordillera Ecozone is the most diverse of Canada's 15 terrestrial ecozones, covering most of British Columbia and a portion of southwest Alberta. This ecozone covers 473,000 square kilometres of Canada, stretching from north-central British Columbia south to the United States border. It encompasses the Alberta Foothills as well as the interior mountain ranges and valleys of B.C., including the Okanagan and the East and East Kootenay valleys.

Resulting from a wide topographical variety, the ecosystems within this ecozone are highly variable and range from alpine tundra and dense conifer forests to dry sagebrush and grasslands. Vegetative cover is extremely diverse. Much of the region is rugged and mountainous. The climate is typified by moderately long, cold winters and short, warm summers. Within this region the climate ranges from sub-arid to arid and mild in southern lower areas to humid and cold at higher elevations in the northern reaches (Ecological Stratification Working Group, 1995; Natural Resources Canada, 2016b).

The Montane Cordillera encompasses two of the four significant agricultural areas of the province; the Creston Valley and the Okanagan Valley. Cattle ranches are prevalent throughout much of the other interior plateau and valley lands. Forestry is the major industry of the lower and middle slopes. Dominant tree species in the Montane Cordillera Ecozone include Douglas fir, lodge pole pine, ponderosa pine and trembling aspen. Mining and tourism are also important economic activities within this ecozone which includes eight National Parks in B.C. and Alberta (Ecological Stratification Working Group, 1995).

2.4.2 Nechako Lakes Electoral District

This section provides information on the Nechako Lakes Electoral District, one of the provincial electoral districts in British Columbia.

Electoral Districts, also called 'regional', 'constituencies', 'wards', 'divisions', 'electorates' or 'ridings', are pre-defined geographical areas upon which Canada's representative democracy is based. One community representative is periodically elected from each district to be part of Canada's legislative body. Nechako Lakes Electoral District located in central BC as depicted in Figure 2.5 and Figure 2.6, is one out of BC's 85 Electoral Districts. It is the scope area of our research and will be used to derive descriptors used for wildfire frequency and location.

Table 2.2 and Figure 2.6 provide basic data of the Nechako Lakes Electoral District which covers the geographic scope of our study area. Statistics Canada periodically conducts census activities using the census boundaries of the regional districts. The Nechako Lakes Electoral District is also a federal Census Division. Census subdivisions aggregate to census divisions, which then aggregate to economic regions, also called development regions. The Nechako Lakes Electoral District covers 8.3% of BC's land area and is sparsely populated with a density of 0.5 person per square kilometer, compared to 4.9 persons/km^2 at a the average provincial level. In 2014, the district's population was 40387 people, with an annual growth rate of 0.40% compared to BC's 0.98% over the period from 2011 to 2014 (BC Statistics, 2013). BC's overall population is expected to grow at an annual rate of 1.3% per year until 2022, after which growth is expected to slow down to below 1.0% until 2036 (BC Statistics, 2013). Most of this growth will be accounted for by the lower mainland region around the provincial capital Vancouver. The population in the Nechako Lakes Electoral District is expected to only grow at an annual rate of 0.1% (BC Statistics, 2014).

Table 2.2 Basic geo- and demographical data of Nechako Lakes Electoral District and BC

Variable	British Columbia	Nechako Lakes Electoral District
Land area (km^2)	944735	78194.4
Land area (%)	100%	8.3 %
Population 2014 (persons)	4631302	40387
Population 2014 (%)	100%	0.9%
Persons / km^2 in 2014	4.9	0.5
Population 2011 (persons)	4499139	39905
Population change (persons)	+ 132163	+ 482
Average annual Population change (%)	+ 0.98 %	+0.40 %
Projected annual growth (%)	1.3%	0.1%

Sources: BC Statistics, 2013; BC Statistics, 2014

The climate in this area in central BC is characterized by short cool summers and cold winters. The tree vegetation is dominated by Engelmann spruce, sub-alpine fir, alpine tundra, central western hemlock and mountain hemlock. Lodge pole pine is a common tree found during regeneration after wildfires.

Figure 2.6 shows some of the main villages and infrastructure in the Nechako Lakes Electoral District. Highway 16 (also named Yellowhead Highway) is the major road connecting the district with the west coast (Prince Rupert) as well as other areas of BC and other provinces. The main human settlements in this District are located along this highway and include Houston, Burns Lake, Fraser Lake and Vanderhoof.

Figure 2.6 Populated areas in the Nechako Lakes Electoral District

Source: BC Electoral Boundaries Commission, 2015

2.4.3 Nadina Forest District

British Columbia is divided into Forest Districts, also known as Natural Resource Districts. The Ministry of Forests, Lands and Natural Resource Operations of British Columbia is responsible for stewardship of provincial crown land and natural resources, as well as protection of BC's archaeological and heritage resources (MFLNRO, 2015abc). Forest Districts are relevant in this study for the selection and comparison of firebreak strategies as explained further in Chapter 3 (methodology).

The delineations of forest districts do not match with those of the BC Electoral District, as depicted in Figure 2.7. As a result, the Nechako Lakes Electoral District covers nine different forest districts either partially or entirely, as further outlined in Table 2.3. The Nadina Natural Resource District is the largest area within the Nechako Lakes Electoral District, covering 40.5% of its total surface or approximately 30,000 square kilometers. This is the area for comparing firebreak strategies with existing management strategies, which will be covered in Chapters 3 through 5 (Nadina Forest District 2006; Nadina Forest District 2009).

The Nechako Lakes Electoral District will be used for historical wildfire data selection as explained in Chapter 3 (methodology). A sub-section of the Nechako Lakes Electoral District called 'the Southside' will be used for the wildfire management planning simulations.

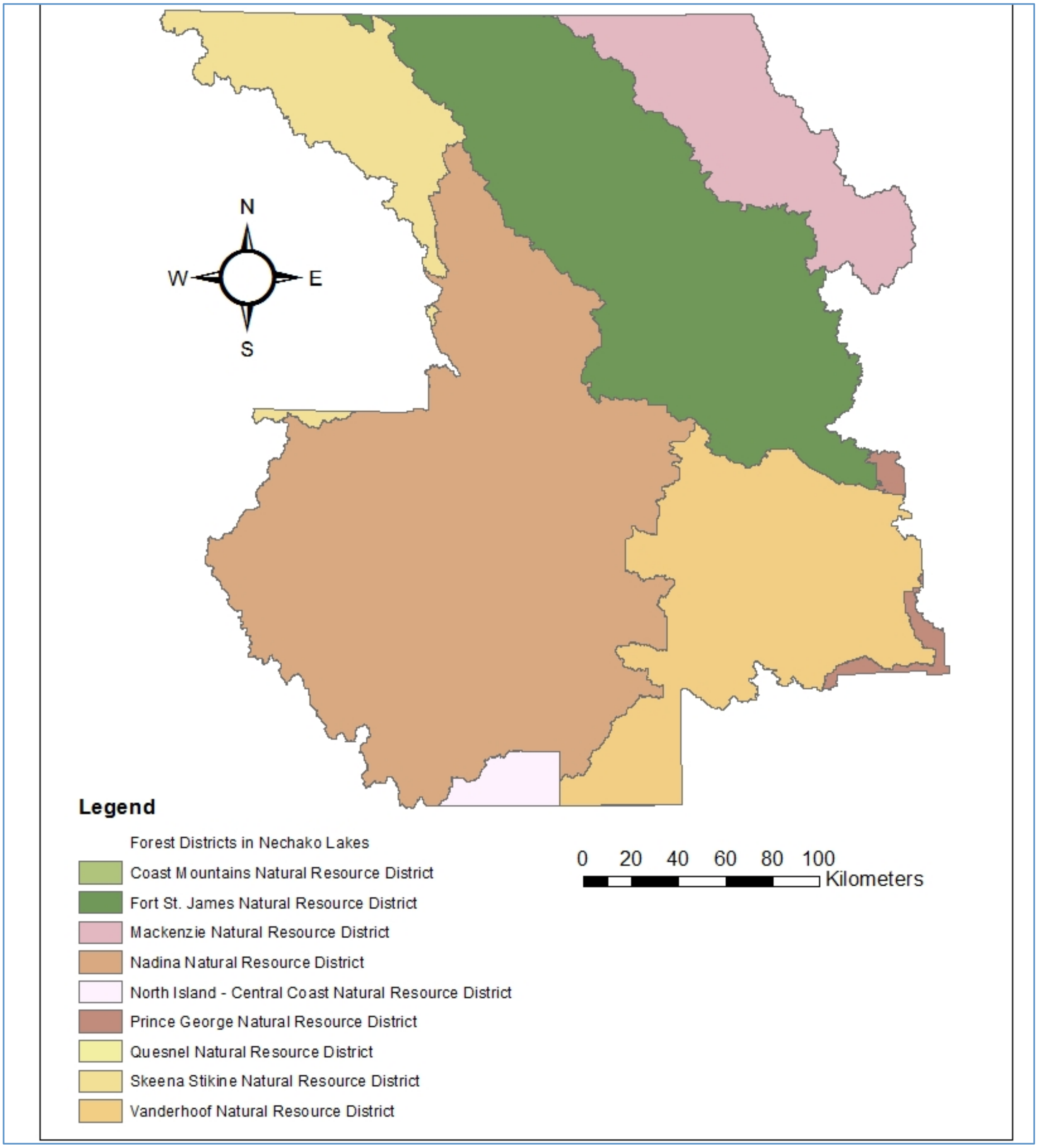


Figure 2.7 Forest Districts intersecting with the Nechako Lakes Electoral District

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

Table 2.3 Forest Districts intersecting within the Nechako Lakes Electoral District

Forest District name	Area (sq. km)	Percentage
Nadina Natural Resource District	29903	40.5%
Fort St. James Natural Resource District	18239	24.7%
Vanderhoof Natural Resource District	11830	16.0%
Mackenzie Natural Resource District	6588	8.9%
Skeena Stikine Natural Resource District	5672	7.7%
North Island - Central Coast Natural Resource District	900	1.2%
Prince George Natural Resource District	651	0.9%
Quesnel Natural Resource District	12	0.02%
Coast Mountains Natural Resource District	0.0006	0.000001%
TOTAL	**73795**	**100%**

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

2.4.4 Lakes and Morice Timber Supply Areas and the Southside

A Timber Supply Area (TSA) is a designated area established by the Ministry of Forests, Lands and Natural Resource Operations of British Columbia in order to practice sound, integrated, resource management principles to improve the sustainability of Allowable Annual Cuts (AAC's). TSAs were originally defined by an established pattern of wood flow from management units to the primary timber-using industries. They are the primary unit for Allowable Annual Cut (AAC) determination. A TSA Supply Block is a designated area within the TSA where the Ministry approves the allowable annual cuts (MLNFRO, 1996; MLNFRO, 2004).

The Nadina Forest District used for comparison of firebreak strategies as described in the previous section and illustrated in Figure 2.7 above, covers all of Morice TSA and Lakes TSA as depicted in Figure 2.8 and Figure 2.9. Lying along the western edge of British Columbia's Interior Plateau, the 1.12-million-hectare Lakes TSA includes the community of Burns Lake. The slightly larger Morice TSA covers 1.5 million hectares, immediately northwest of the Lakes TSA and includes the communities of Houston and Granisle. The topography of the area is rolling and gentle to the north and east, and more mountainous in the southwest. It is also characterized by a high concentration of lakes. Both timber supply areas are bordered by Tweedsmuir Provincial Park to the south, and are covered by a number of water bodies. These include three major rivers (Bulkley, Morice, and Nadina) and three major lakes: Babine, in the north (the longest and largest freshwater lake in British Columbia), and Francois and Ootsa lakes (part of the Nechako Reservoir) in the south.

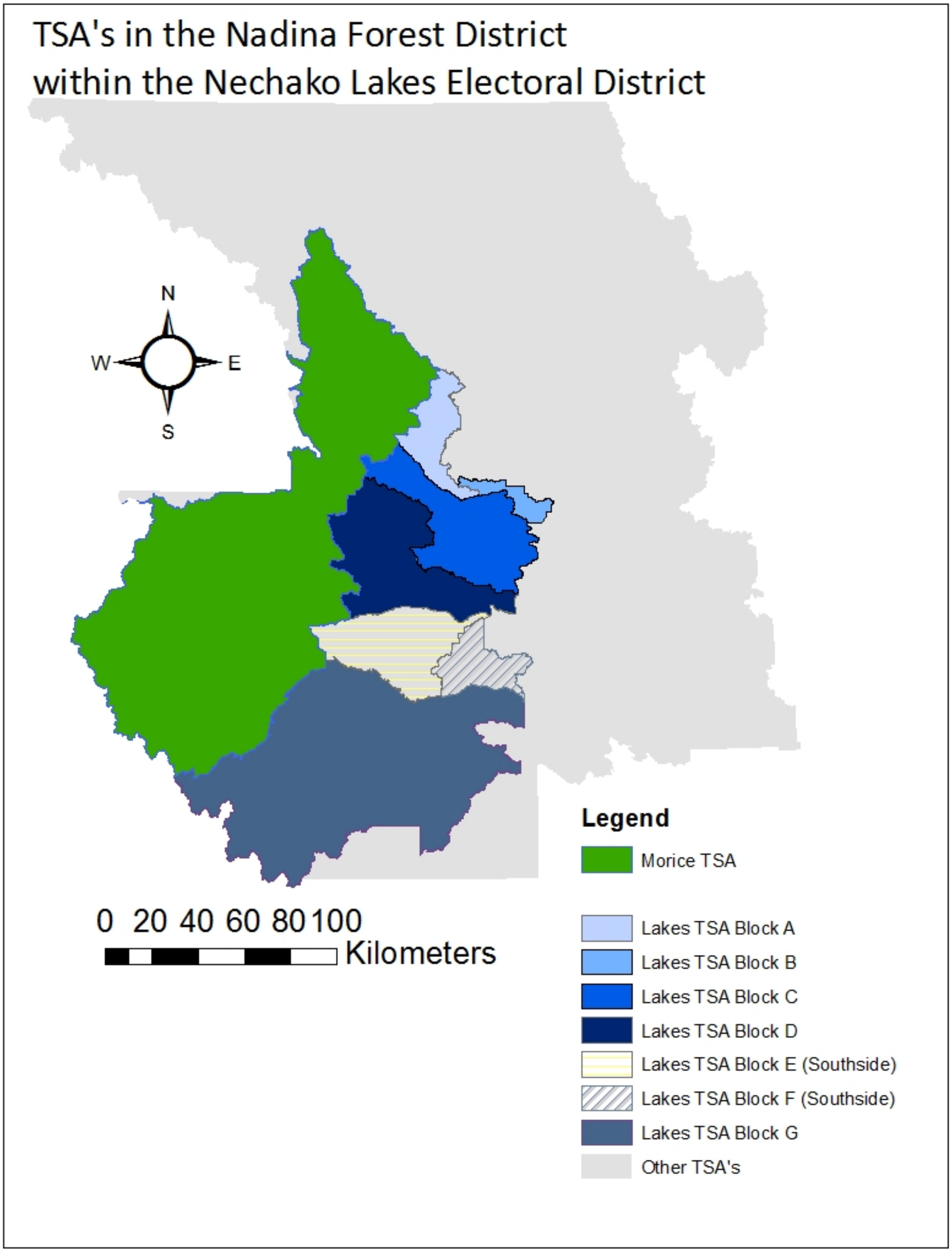


Figure 2.8 Morice TSA and Lakes TSA constituting the Nadina Forest District
Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

The 'Southside' which is the subject of the various simulations executed in this thesis, is the area between Francois Lake and Ootsa Lake as shown in Figure 2.8 and Figure 2.9 which show that the Southside roughly covers Block E and F of the Lakes TSA. The Southside covers numerous accessible and remote lakes, large farms, ranches and dense forests with panoramic views of the snow-capped mountains to the southeast. Forestry, tourism and farming form the main sources of income on the Southside. Its population is approximately 2000 spread across a number of hamlets and reserves as well as remotely residing on farms, acreages and reserves throughout the area.

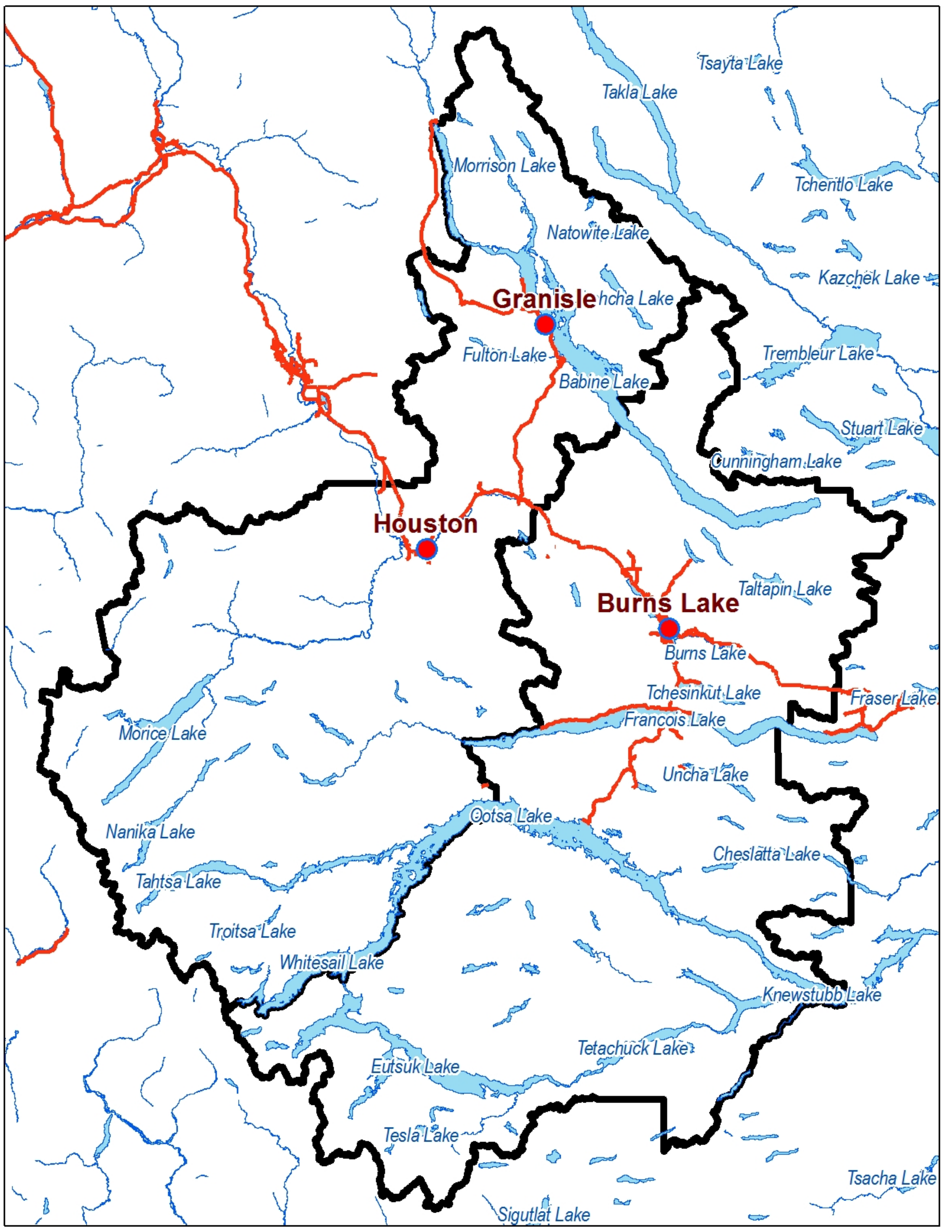


Figure 2.9 Nadina Forest District
Source: MFLNRO, 2015c

2.4.5 Land Use

Table 2.4 provides descriptions of land use types as documented by the Government of British Columbia (www.data.gov.bc.ca). The age range of the young forest is defined to be less than 140 years old and greater than 6 metres in height, but which has not recently or selectively been logged. After this time period (140 years) they become old forests.

Table 2.4 Land use descriptions

Land use	Description
Young Forest	Forest less than 140 years old and greater than 6 metres in height. Areas defined as Recently Logged and Selectively Logged land uses are excluded from this class.
Old Forest	Forest greater than or equal to 140 years old and greater than 6 metres in height. Areas defined as Recently Logged and Selectively Logged land uses are excluded from this class.
Recently logged	Timber harvesting within the past 20 years
Fresh Water	Fresh Water bodies
Alpine	Areas virtually devoid of trees at high elevations.
Wetlands	Wetlands including swamps
Agriculture	Land based agricultural activities undifferentiated as to crop (i.e. land is used as the producing medium).
Sub Alpine Avalanche Chutes	Areas below the tree line that are devoid of forest growth due primarily to snow avalanches. Usually herb or shrub covered.
Glaciers and Snow	Glaciers and permanent snow. Depending on the date of imagery
Selectively logged	Areas where the practice of selective logging can be clearly interpreted on the Landsat TM image and TRIM aerial photography.
Shrubs	Naturally occurring shrub cover with at least 50% coverage. NOT wetlands
Recently burned	Areas virtually devoid of trees due to fire within the past 20 years. Forest less than or equal to 15% cover
Barren Surfaces	Rock barrens
Urban	All compact settlements including built up areas of cities
Range Lands	Unimproved pasture and grasslands based on cover rather than use. Cover includes drought tolerant grasses.
Mining	Land used now (or in the past and remains unclaimed or reclaimed for the surface extraction of minerals or quarry materials.
Recreation activities	Land used for private or public outdoor recreational purposes. Ski resorts and golf courses are included. This class does not include recreational areas within built-up portions of cities
Resid. Agric. Mixtures	Timber harvesting within the past 20 years

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

Table 2.5 specifies the land use metrics of the Nechako Lakes Electoral District and the Southside. These data are presented visually in Figure 2.10. In the dataset analyzed, young forest covers 52.08% of the Southside as compared to 39.97% in the Nechako Lakes Electoral District. Old forest is relatively underrepresented with 15.81 of land cover in the Southside in comparison to 31.53 in the Nechako Lakes Electoral District. The Southside had a slightly higher percentage of recently logged areas (11.49%, versus 7.62% in the Nechako Lakes Electoral District). Another observation is that the presence of Francois Lake and numerous other smaller lakes contribute to a relatively high coverage of fresh water with 11.49% of fresh water in the Southside and only 6.22% in the Nechako Lakes Electoral District.

Table 2.5 Land use metrics of Nechako Lakes Electoral District and the Southside

Land use	**Nechako Lakes Electoral District**		**Southside**	
	km^2	**%**	**km^2**	**%**
Young Forest	29498.57	39.97%	1233.5	52.08%
Old Forest	23267	31.53%	374.5	15.81%
Recently Logged	5622.99	7.62%	272.2	11.49%
Fresh Water	4587.31	6.22%	28.2	11.89%
Alpine	4023.45	5.45%	0	0%
Wetlands	2697.7	3.66%	64.4	2.72
Agriculture	1142.06	1.55%	110.2	4.65%
Sub alpine Avalanche Chutes	818.2	1.11%	0	0%
Glaciers and Snow	577.42	0.78%	0	0%
Selectively Logged	437.44	0.59%	4.2	0.18%
Shrubs	374.74	0.51%	0	0%
Recently Burned	275.38	0.37%	0	0%
Barren Surfaces	224.65	0.30%	10.4	0.44%
Urban	113.05	0.15%	3.2	0.13%
Range Lands	66.55	0.09%	11.1	0.47%
Mining	43.36	0.06%	0.5	0.02%
Recreation Activities	15.28	0.02%	0.7	0.03%
Residential Agriculture Mixtures	10.18	0.01%	2.2	0.09%
Total	**73795.30**	**100%**	**2368.44**	**100%**

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

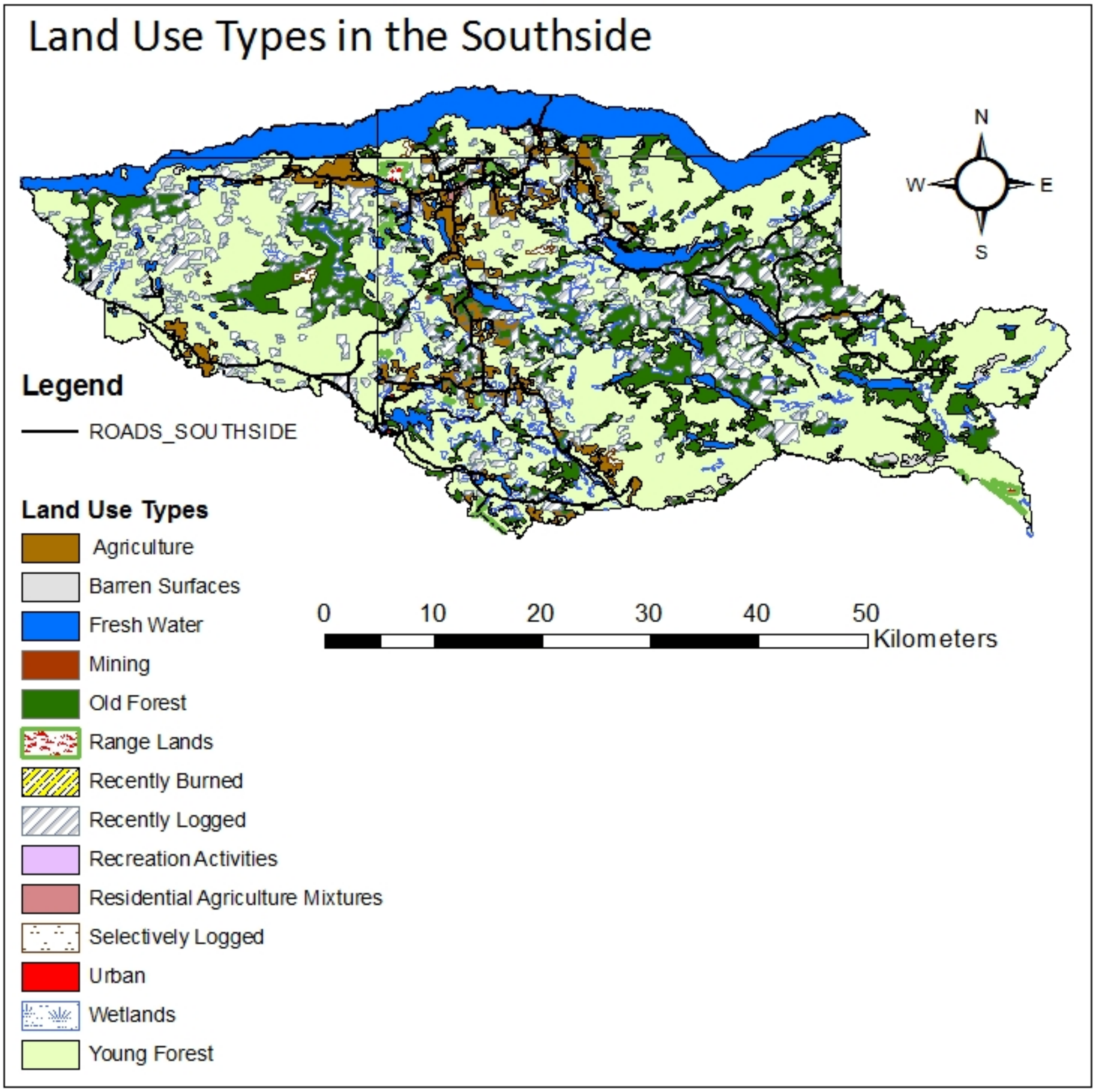


Figure 2.10 Land Use Types in the Southside

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

2.4.6 Land Ownership

Table 2.6 provides an overview of land ownership codes applicable to the Nechako Lakes Electoral District along with their proportional distribution. Figure 2.11 presents the distribution of land ownership in the Southside. Privately owned land comprises only 3.56% or 2628 square kilometers of the total surface, and is located around the major towns on the Yellowhead Highway, namely Houston, Rose Lake, Fraser Lake and Burns Lake. The balance is mostly Crown Land with different schedules and allocations. Appendix A (Land Ownership and Schedule Codes) specifies the Land Ownership and Schedule Codes in more detail. Tweedsmuir Provincial Park is partially located within the Nechako Lakes Electoral District and forms over half of the 14% of the land surface dedicated to provincial parks.

Table 2.6 Land ownership of Nechako Lakes Electoral District and the Southside

Land Ownership Description	**Code**	**Nechako Lakes Electoral District**		**Southside**	
		km²	**%**	**km²**	**%**
Crown grants - prov adm. – Forest Man. unit (TSA)	62	56415	76.45%	1553.54	65.59
Crown - prov. Admin – Prov. Park Class A	63	10436	14.14%	78.54	3.32
Privately owned land	40	2628	3.56%	337.84	14.26
Community Forest	79	2275	3.08%	251.68	10.63
Crown – Awarded Woodlot licence (Schedule 'B' land. Private portion, Schedule 'A', is coded 40-N).	77	1085	1.47%	133.32	5.63
Crown (N<100ha>C) Miscellaneous reserves, with or without O.I.C.s: ; Forest Service Recreation Reserve/Corridor (not incl. Forest Recreation Trails	69	456	0.62%	0.04	0.002
Federal Lands (reserves, parks and Dominion Govt. Blocks)	52	211	0.29%	8.84	0.37
Crown – BMTS (Biodiversity, Mining and Tourism Area)	68	146	0.20%	0.36	0.02
Crown (N<100ha>C) – UREP (Use, Recreation and Enjoyment of the Public) Reserves	61	77	0.10%	4.28	0.18
Crown land adm. by the Govt of BC other than active leases or permits	64	41	0.06%	-	-
Crown grants – prov. administration	60	17	0.02%	-	-
Crown land administered by the Government of British Columbia other than active leases or permits	65	5	0.01%	-	-
Crown land administered by the Government of British Columbia under active lease and permits.	99	2	0.00%	-	-
Crown – Schedule 'B' land, TFL, where ownership status complete	72	1	0.00%	-	-
Total		**73795**	**100 %**	**2368.44**	**100 %**
Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca					

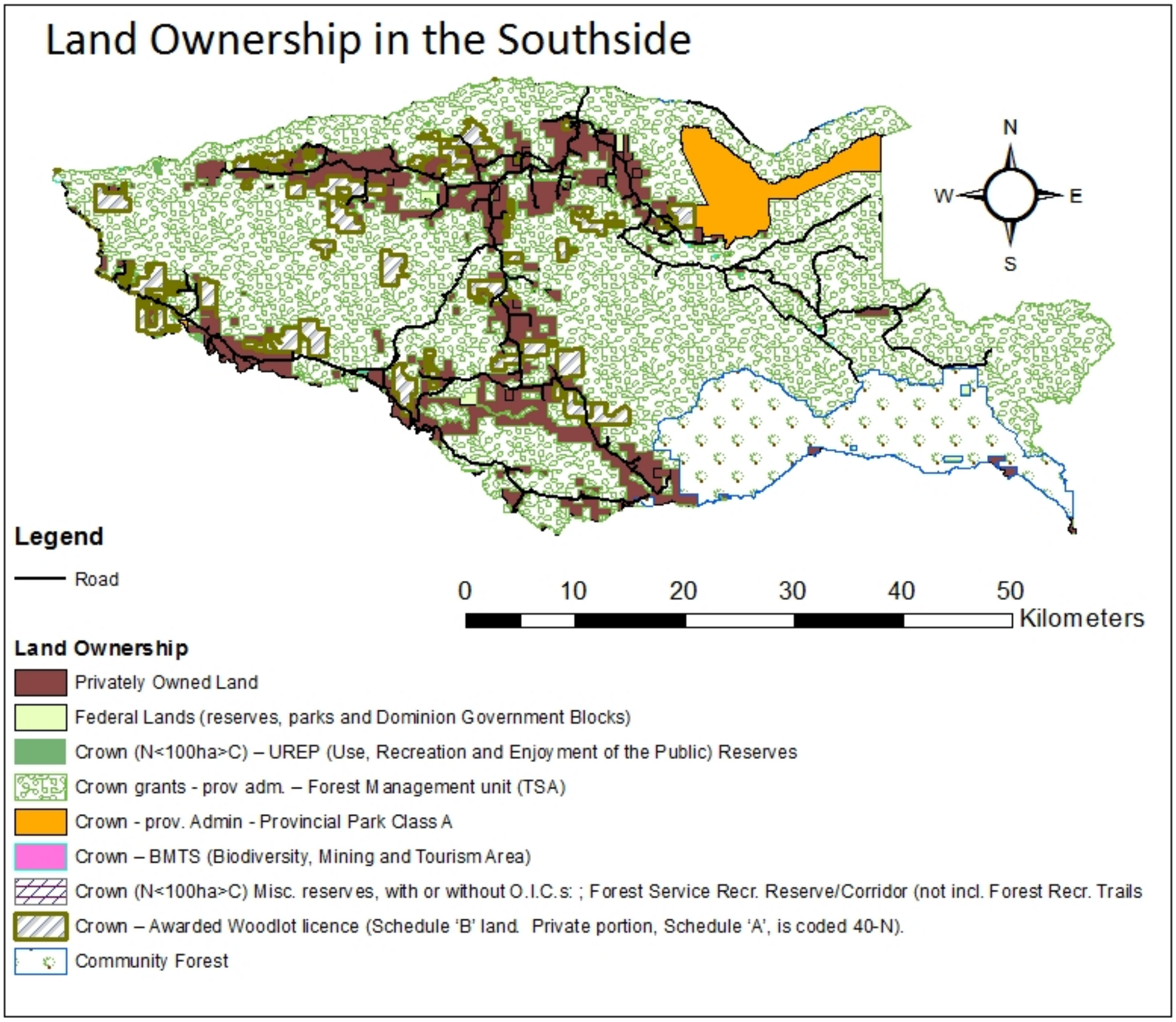


Figure 2.11 Land Ownership in the Southside

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

2.4.7 Regional socio-economic indicators

Table 2.7 provides baseline socio-economic data for the Nadina Forest District in which the Southside is located. In 2005, forestry activities provide 47.6% of the gross revenues in the Nadina Forest District, as compared to a provincial level of 6.1%. Agricultural revenue is nearly negligible in the district with 0.5% of total revenues, while BC's average is 1.9%. On the other hand, tourism contributes significantly (5.7%) to total revenues (BC's average is 4.7%).

The relative significance of forestry, and to some extent tourism activities in the district is reflected by the other economic indicators including net regional product, royalties, indirect taxes, gross wages and number of employment positions. These indicators also confirm the relative contribution of agricultural activities to the economy in the Nadina Forest district.

Table 2.7 Socio-economic data for the Nadina Forest District

Sector	Nadina Forest District		B.C.	
	Gross revenue ($M)	% of total	Gross revenue ($M)	% of total
Agriculture	5.4	0.5	5 540.1	1.9
Forestry	508.8	47.6	17 623.7	6.1
Service	13.4	1.3	141 137.4	49.1
Public	61.4	5.7	37 687.7	13.1
Visitor	133.9	12.5	13 573.5	4.7
Rest of the economy	346.2	32.4	71 949.7	25.0
Total	1 069.3	100.0	287 512.2	100.0
	Net regional product ($M)	% of total	Net regional product ($M)	% of total
Agriculture	1.5	0.4	1 819.9	1.6
Forestry	240.0	59.5	7 999.1	7.2
Service	9.6	2.4	54 129.1	49.0
Public	36.6	9.1	22 535.6	20.4
Visitor	34.0	8.4	5 586.2	5.1
Rest of the economy	81.8	20.3	18 414.2	16.7
Total	403.6	100.0	110 484.2	100.0
	Royalties and indirect taxes ($M)	% of total	Royalties and indirect taxes ($M)	% of total
Agriculture	0.6	0.6	598.7	2.3
Forestry	88.3	83.7	2 453.5	9.4
Service	1.7	1.7	18 386.3	70.2
Public	6.9	6.6	1 732.0	6.6
Visitor	2.8	2.7	703.1	2.7
Rest of the economy	5.1	4.8	2 304.4	8.8
Total	105.5	100.0	26 178.0	100.0
	Gross wages ($M)	% of total	Gross wages ($M)	% of total
Agriculture	0.7	0.3	625.6	1.1
Forestry	113.5	49.0	4 191.7	7.3
Service	7.6	3.3	18 127.8	31.5
Public	24.2	10.4	18 319.9	31.8
Visitor	25.0	10.8	4 414.4	7.7
Rest of the economy	60.8	26.2	11 921.9	20.7
Total	231.7	100.0	57 601.3	100.0
	# of employment positions	% of total	# of employment positions	% of total
Agriculture	190	1.9	85 080	4.2
Forestry	2 495	24.5	98 280	4.9
Service	816	8.0	502 240	24.9
Public	865	8.5	470 750	23.4
Visitor	2 262	22.2	256 400	12.7
Rest of the economy	3 549	34.9	601 860	29.9
Total	10 178	100.0	2 014 610	100.0

Source: Patriquin, et al, 2005

2.4.8 Cultural and heritage aspects of the Southside

The Southside has long been home to the Nee Tahi Buhn, Skin Tyee and Cheslatta First Nation peoples. The Cheslatta Carrier Nation has a long, well documented history in the area. Today, their traditional territory is centered on Cheslatta Lake. However, much of their territory, including Cheslatta Village, was lost due to the flooding of the area for the construction of the Kenny Dam in 1952.

An end to their long battle to achieve justice over their forced relocation was forged on January 30, 2012, when elder and former Cheslatta Carrier Nation Chief Abel Peters paid Rio Tinto Alcan $6 in cash for the return of nearly 12,000 acres of land that Rio Tinto Alcan had acquired as a result of the 1950's Kemano I project. The land included old Cheslatta village sites. After 60 years, the Cheslatta people once again own their homelands outright. During the ceremony, Abel Peters fired three rifle shots signalling the 'Return of the Spirits'. Several hundred people witnessed two local priests bless the remaining cemetery and Cheslatta Lake. These are the resting places for over 60 graves that have been washed away since 1952 (Robertson, 2012).

Most Cheslatta members now live on a dozen small, scattered reserves just south of Francois Lake. The band office and other community buildings are located two kilometres south of the Southbank ferry dock. Today the Cheslatta operate the Chief Louie Paddle Company and use reclaimed flood lumber from the depths of Ootsa Lake to craft paddles and keepsakes carved by their elders for local and overseas markets (SEDA, 2016).

2.4.9 Context of wildfire fuel management in the Nadina Forest District

The Nadina Forest District has made significant efforts in implementing a forest health strategy based on the province-wide Forest and Range Practices Act and the Forest Planning and Practices Regulation. Maintaining species diversity is a key element in retaining resilience and preserving potential of regenerating stands of a healthy forest (Nadina Forest District, 2009). The mountain beetle infestation in the Nadina Forest District has drastically impacted the landscape and forest practices and mandated the implementation of temporary increases of Annual Allowable Cuts (AAC) granted to licensees (Patriquin et al, 2005). Figure 2.12 shows the regional forest licensees that are potentially affected by changes in forest and fuel management practices and AAC quota.

In October 2002, the AAC for the Morice TSA was set at 1.961 million cubic metres. In February 2008 it was temporarily increased to 2.165 million cubic metres to obtain maximum economic values and enable faster regeneration of areas already affected by the mountain pine beetle. In March 2015, it was decided that the AAC for the Morice TSA would be reduced to 1.6 million cubic metres by March 16, 2020. This will allow for sufficient time to clear out remaining areas of dead pine, spruce and balsam, before these trees will be degraded to the point that they will not have harvestable value (MFLNRO, 2015abc).

In 1982, the AAC for the Lakes TSA was set at 1.5 million cubic metres. This level was confirmed in 1987 and again in 1996. In August 2001, the Lakes TSA AAC was increased to 2.962 million cubic metres with the goal of reducing the fuel loads and future damages resulting from an unprecedented mountain pine beetle infestation in the area (MFLNR, 2004). On October 2012, the AAC was reduced to 1.975 million cubic metres until further notice.

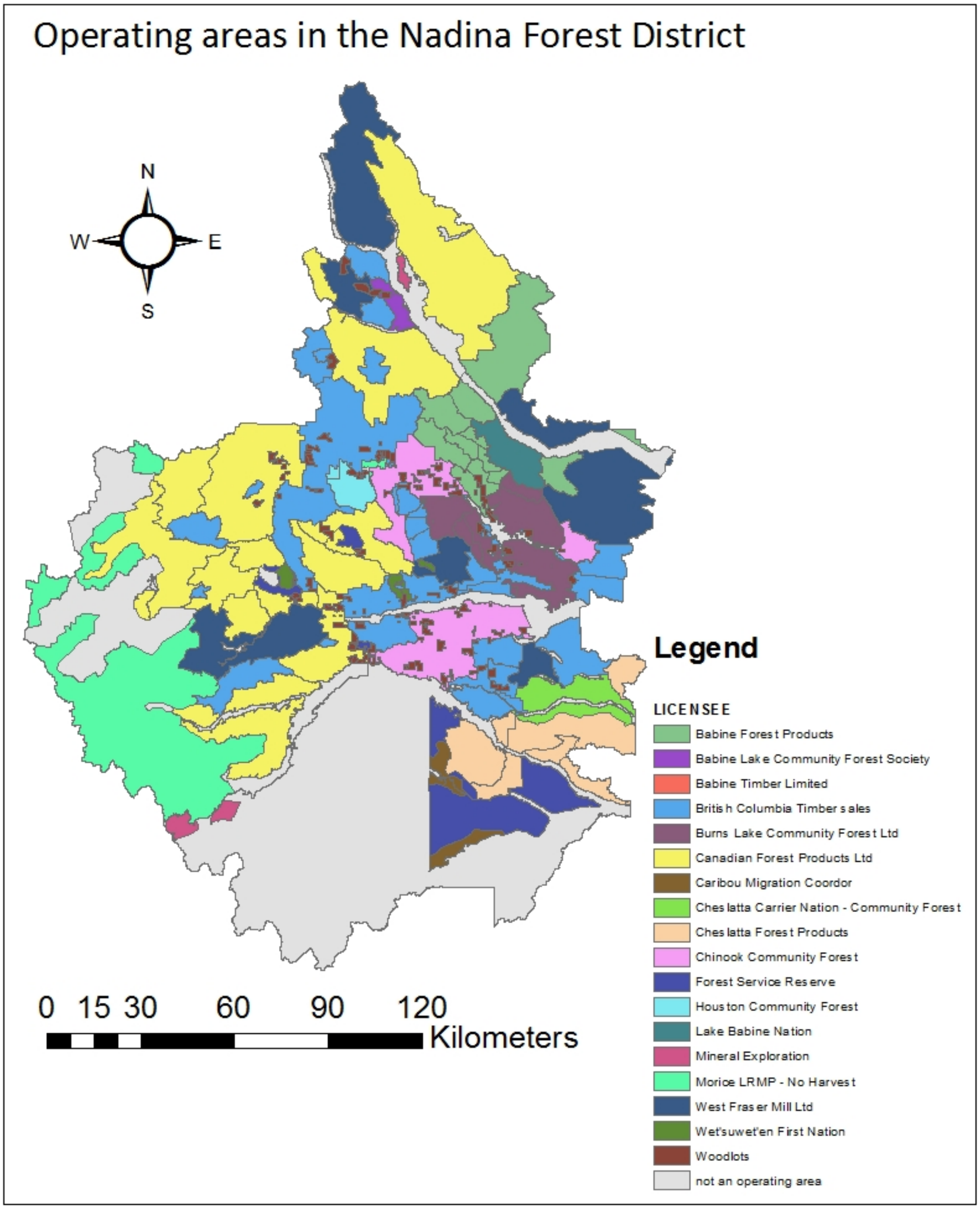


Figure 2.12 Operating Areas in the Nadina Forest District

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

2.5 Software Applications in Wildfire Simulation Modelling in Canada

Mathematical wildfire simulation models have been developed and applied extensively in increasing understanding of wildfire behaviour and ultimately in the support of decision making and policy development in different countries (Ager and Finney, 2009; Mladenoff and Baker, 1999; Parisien et al, 2005; Parisien et al, 2006; Parisien et al, 2010; Pastor et al, 2003).

Various categorizations can be made across these models. They can be defined as either deterministic or stochastic, spatial or non-spatial, and vector or cellular. Deterministic models define the spread of wildfire by using a mathematical modelling system. Given a certain set of parameters their outcome will be replicable, meaning that simulation results can be directly compared to inputs. Stochastic models on the other hand use probability density functions as inputs and will have a different outcome with every simulation (Finney, 1999).

Out of all wildfire simulation model applications developed in Canada, a set of models has emerged which has been applied most successfully in British Columbia for understanding and predicting wildfire behaviour. Figure 2.13 illustrates the general usage of each of these models for different purposes.

The following sections provide a brief description of these and related software applications to the extent they are used in this thesis. These include ArcGIS, *Mathwave Easyfit*, Prometheus, Burn P3 and Pandora.

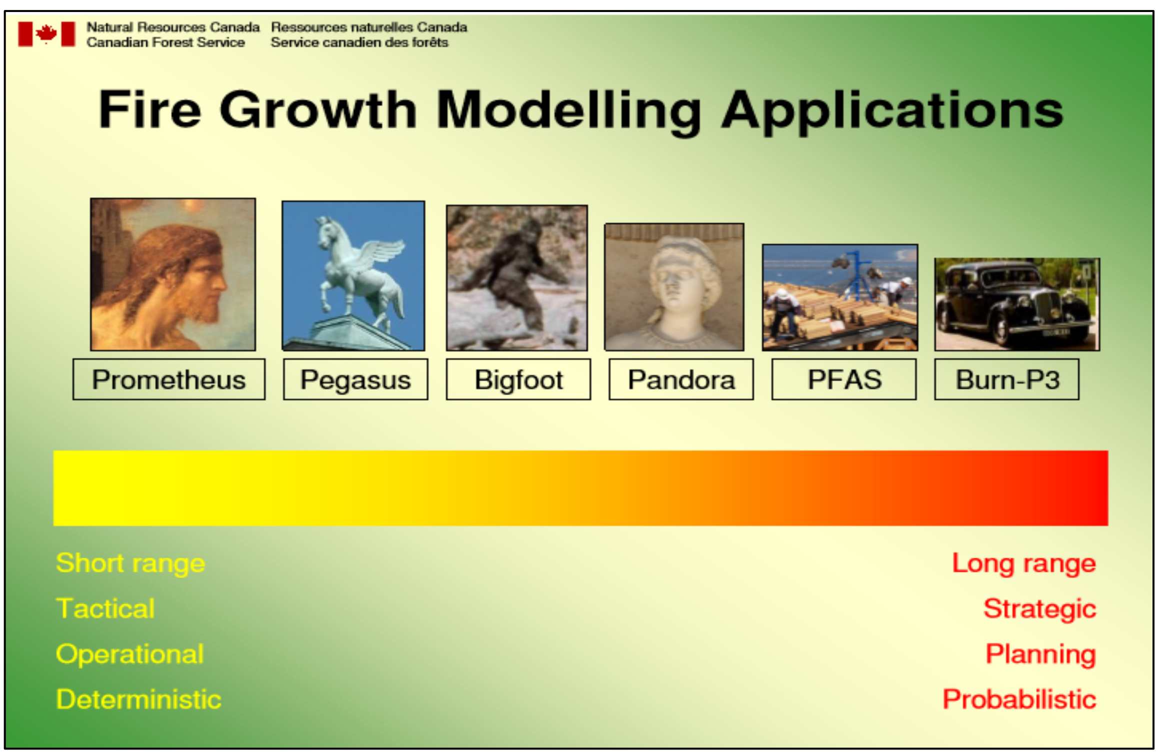


Figure 2.13 Wildfire Growth Modelling Applications
Source: Englefield, 2014

2.5.1 GIS and ArcGIS

The first known use of the term 'geographic information system' or **GIS** was by the Canadian scientist Roger Tomlinson in the year 1968 (Tomlinson, 1968). The term describes an information system used to integrate, store, edit, analyze and share geographic information. Geographic information science is the science underlying geographic concepts, applications, and systems (Goodchild, 2010).

ArcGIS is a geographic information system (GIS) software developed by the Environmental Systems Research Institute (ESRI) based in Redlands, California, U.S.A. It is a scalable system used for discovering, analyzing, creating, compiling and sharing geographic information. Maps and geographic information is used in a range of applications and managed in a relational database. The software provides an infrastructure for making maps and geographic information available throughout an organization, across a community, and openly on the Web. The product is available as a server-based product, or can be run on a personal computer. Extensions are available and can be installed in the form of Toolsets. One example of a Toolset is Spatial Data Modeller (SDM). This is a collection of geo-processing tools for adding categorical maps with interval, ordinal, or ratio scale maps to produce a predictive map of where something of interest is likely to occur. The tools include various data-driven methods and have help files that include references to publications discussing the applications of the methods implemented in each tool. Several of the tools create output rasters, tables, or files. New additions also include step-by-step tutorials, innovative validation tools and new modelling tools (ESRI, 2016).

2.5.2 Mathwave Easyfit

Mathwave EasyFit is a data analysis and simulation application allowing to fit probability density functions to sample data, select the best model, and apply the analysis results to make better decisions. *EasyFit* can be used as a stand-alone Windows application or with *Microsoft Excel* and other third party *Excel*-based simulation tools, leaving the complex technical details behind the scenes and enabling the end user to focus on business goals (Mathwave, 2016).

Mathwave EasyFit combines the classical statistical analysis methods and innovative data analysis techniques, making it a tool of choice for anyone dealing with probability data. Product features are offered through an easy to use interface and include support for more than 50 continuous and discrete distributions, powerful automated fitting mode combined with flexible manual fitting capability. Its functionality also includes interactive graphs, goodness of fit tests and random number generation. *EasyFit* integrates into the main menu of *Microsoft Excel*, allowing for data analysis and simulation within *Excel*. It provides more than 650 additional *Excel* worksheets and VBA functions which can be used to carry out advanced probability calculations such as Monte Carlo simulation. It enables the user to analyze large data sets (up to 250,000 data points), improve the validity of models by applying the advanced distributions. It offers the user to calculate descriptive statistics, enter and manipulate data using an *Excel*-like worksheet, organize data and analysis results, view distribution graphs and explore their properties without entering the data. Results can be exported in multiple formats.

2.5.3 Prometheus and PrometheusCOM

Prometheus is a deterministic wildfire fuel growth simulation model based on the Fire Weather Index (FWI) and Fire Behaviour Prediction (FBP) sub-systems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner, 1987; Forestry Canada, 1992). The model computes spatially-explicit fire behaviour and spread outputs given heterogeneous fuel, topography and weather conditions. Spatial outputs are generally compatible with Geographic Information Systems (Hirsch, 1996; Pearce, 2009; Tymstra et al, 2010; Van Wagner, 1987). Landscape rasters which are used as (optional) inputs into the model include: FBP fuel, elevation, slope, aspect, degree of curing, green-up, percent conifer, percent dead fir, crown base height and tree height.

Potential applications of Prometheus include:

- Forecasting wildfire fuel growth for operational decision support.
- Assessing the effectiveness of alternative fuel management strategies.
- Planning prescribed burns.
- Providing forensic support for wildfire investigations.
- Studying the role of fire in establishing and maintaining landscape patterns.
- Providing spatial and temporal estimates of smoke emissions.
- Examining the impact of climate change strategies on area burned.
- Supplementing fire behaviour training and education programs.

Table 2.8 and Table 2.9 list the standard Canadian FBP fuel types used in Prometheus, along with their default parameter values, which can be modified if required. Explanatory information about Prometheus, the ASCII file format and Projection files is provided in respectively Appendix B (Prometheus File Formats and GIS Compatibility), Appendix C (ASCII Raster File Data) and Appendix D (Projection File).

Table 2.8 Fuel types in the Canadian Forest Fire Behaviour Prediction System

General category	Fuel type designation	Fuel type
Coniferous	C-1	Spruce–Lichen Woodland
Coniferous	C-2	Boreal Spruce
Coniferous	C-3	Mature Jack Pine or Lodgepole Pine
Coniferous	C-4	Immature Jack Pine or Lodgepole Pine
Coniferous	C-5	Red and White Pine
Coniferous	C-6	Conifer Plantation
Coniferous	C-7	Ponderosa Pine/Douglas-fir
Deciduous	D-1	Leafless Aspen
Deciduous	D-2[b]	Leafed Aspen
Mixedwood	M-1	Boreal Mixedwood—Leafless
Mixedwood	M-2	Boreal Mixedwood—Green
Mixedwood	M-3	Dead Balsam Fir/Mixedwood—Leafless
Mixedwood	M-4	Dead Balsam Fir/Mixedwood—Green
Slash	S-1	Jack Pine or Lodgepole Pine Slash
Slash	S-2	Spruce/Balsam Slash
Slash	S-3	Coastal Cedar/Hemlock/Douglas-fir Slash
Open	O-1a[c]	Matted Grass
Open	O-1b[c]	Standing Grass

[a]Source: Hirsch (1996).
[b]Fuel type variant based only on expert opinion.
[c]Variants of the O-1 fuel type.

Source: Forestry Canada, 1992

Table 2.9 Canadian Forest Fire Behaviour Prediction System customizable fuel type parameters

Fuel type	a_{ROS}[a]	b_{ROS}[a]	c_{ROS}[a]	BUI_0[b]	q[c]	Max. BE[d]	CBH[e] (m)	CFL[f] (kg/m^2)
C-1	90	0.0649	4.50	72	0.90	1.076	2.0	0.75
C-2	110	0.0282	1.50	64	0.70	1.321	3.0	0.80
C-3	110	0.0444	3.00	62	0.75	1.261	8.0	1.15
C-4	110	0.0293	1.50	66	0.80	1.184	4.0	1.20
C-5	30	0.0697	4.00	56	0.80	1.220	18.0	1.20
C-6	30	0.0800	3.00	62	0.80	1.197	7.0	1.80
C-7	45	0.0305	2.00	106	0.85	1.134	10.0	0.50
D-1	30	0.0232	1.60	32	0.90	1.179	NA[k]	NA
M-1/M-2[g]	C-2 110 D-1 30	C-2 0.0282 D-1 0.0232	C-2 1.50 D-1 1.60	50	0.80	1.250	6.0	0.80
M-3[h]	M-3 120 D-1 30	M-3 0.0572 D-1 0.0232	M-3 1.40 D-1 1.60	50	0.80	1.250	6.0	0.80
M-4[h]	M-4 100 D-1 30	M-4 0.0404 D-1 0.0232	M-4 1.48 D-1 1.60	50	0.80	1.250	6.0	0.80
O-1a[ij]	190	0.0310	1.40	1	1.00	1.000	NA	NA
O-1b[ij]	250	0.0350	1.70	1	1.00	1.000	NA	NA
S-1	75	0.0297	1.30	38	0.75	1.460	NA	NA
S-2	40	0.0438	1.70	63	0.75	1.256	NA	NA
S-3	55	0.0829	3.20	31	0.75	1.590	NA	NA

[a]Rate-of-spread (ROS) parameter value specific to each fuel type. a_{ROS}, b_{ROS}, and c_{ROS} parameters for M-3 and M-4 fuel types apply when the percentage of dead fir is 100%.
[b]*BUI* = Buildup Index.
[c]*q* = proportion of maximum rate of spread at *BUI* equal to 50.
[d]*BE* = Buildup Effect.
[e]*CBH* = crown base height.
[f]*CFL* = crown fuel load.
[g]Variable % conifer values apply for the M-1 and M2 fuel types.
[h]Variable % dead fir values apply for the M-3 and M-4 fuel types.
[i]Variable % grass cure values apply for O-1a and O-1b fuel types.
[j]Variable grass fuel load values (kg/m^2) apply for the O-1a and O-1b fuel types.
[k]NA= not applicable.

Source: Van Wagner, 1987

Prometheus is engineered using five separate common object models, also called COMs. A COM is *Microsoft Windows* programming standard that allows object-oriented components to be re-used in different software applications and languages without sharing source code. Prometheus uses this component-based software architecture. The important principles of COM include reuse of the component objects, interoperability of the binary standard, and allowance for distributed capabilities. The COMs developed for Prometheus are called low-level interfaces and are named *FuelCOM*, *FWICOM*, *GridCOM, FireEngine* and *WeatherCOM*. To facilitate the use of these low-level interfaces, an umbrella or wrapper COM was developed. This high-level interface is called *PrometheusCOM*. It provides a more user-friendly interface for programmers to communicate with the low level COMs. Examples of software applications that integrate *PrometheusCOM* components include Burn-P3, Pandora, Pegasus, and SFMS.

Prometheus uses Huygens' Principle of wave propagation (Huygens, 1690). Appendix B (Prometheus File formats and GIS Compatibility) contains information about the mathematical approach used by the Prometheus model. Prometheus is the result of a national project endorsed by the Canadian Interagency Forest Fire Centre and its members. Alberta Environment and Sustainable Resource Development is now the lead agency and custodian of Prometheus. The Canadian Forest Service maintains Burn-P3 and Pandora in collaboration with forest and fire management agencies across Canada.

2.5.4 Burn-P3

Burn-P3 (probability, prediction, and planning) is a windows-based software application for a spatial fire simulation model that is used for land-management planning and wildfire fuel research. It uses the Prometheus fire-growth engine to simulate the ignition and spread of a very large number of fires. It is used to evaluate the fire likelihood or burn probability (BP) of a large fire-prone landscape. The inputs to Burn-P3 consist of fuels (e.g., vegetation), topography, weather, and patterns of fire ignitions. Its main output is a surface of fire probabilities, or burn probability map. Burn-P3 is capable of computing burn probabilities for large landscape, and produces additional outputs, such as fire intensity maps, fire statistics and simulated fire perimeters (Natural Resources Canada, 2014; Parisien et al., 2005).

The modeled entities used in this model are individual grid cells (i.e., pixels). The state variables used in the simulation of each fire in Burn-P3 are found in Table 2.10. They can be partitioned into those that are intrinsically spatial (spatial units) and those that affect the entire fire indiscriminately of space (environment). Note that many of the state variables used in Burn-P3 are optional.

Table 2.10 Burn P-3 State Variables

Class	Name	Data type	Description[A]
Spatial units	Fuels	Raster grid (nominal)	Canadian Forest Fire Behavior Prediction System fuel types and non-fuel features
	Topography[B]	Raster grid (numeric)	Elevation (m)
	Ignition location	Raster grid (numeric)	Relative probability of ignition (unitless); ignitions can be spatially structured or completely random
	Fire zones[B]	Raster grid (nominal)	Geographic zones with distinct fire regimes
	Weather zones[B]	Raster grid (nominal)	Geographic zones with distinct fire weather
	Wind grids	Raster grid (numeric)	Influence of topography on wind direction (degrees) and wind speed (km/h) for the eight main cardinal directions
	Vectorized firebreaks	Vector shapefiles (nominal)	Linear features of a specified width that interrupt fire spread (can be breached if specified)
Environment	Seasons[B]	Setting (nominal)	Start and stop dates of periods for which fire weather, grass curing, and green-up change
	Causes[B]	Setting (nominal)	The cause of fire ignition; the spatial patterns by cause may vary by season
	Fire duration (i.e., Spread-event days)	Frequency distribution (numeric)	Number of spread-event days per fire (i.e., duration of burning) (number of days); a single (i.e., constant) value can be specified for each fire
	Daily fire weather conditions	List of burning conditions (numeric)	Daily fire station weather at noon local standard time and associated Fire Weather Index System components (Van Wagner 1987); list is partitioned by season and weather zone; daily weather conditions for fires spreading for >1 day may be sampled sequentially or randomly from the fire weather list

[A]Units included in parenthesis for numeric variables
[B]Denotes optional state variables

Sources: Natural Resources Canada, 2014; Parisien et al, 2005

The spatial units consist of fuels, topography, ignition location, fire zones, weather zones, wind grids, and vectored firebreaks. The fuels variable consists of a classification of fuel types based on vegetation attributes. Each fuel type has a characteristic fire behaviour that varies according to weather and topography. Pixels that do not burn (e.g., open water, exposed rock) are considered "non-fuel."

Figure 2.14 shows the attribute table of the fire behaviour prediction (FBP) module used by Prometheus, Burn-P3 and Pandora, of each of the default fuel types. All values used in the fuel grid must correspond to values in this table.

Topography modifies the fire behaviour by vectoring the wind speed as a function of slope. The ignition location variable represents a spatially weighted probability of experiencing an ignition at any given point on the landscape; these probabilities may vary by season and cause. The fire zones stratify the landscape in areas of distinct fire regimes, as modeled in Burn-P3. The weather zones represent areas of distinct fire weather conditions with which fire growth is simulated. The wind grids modify the input wind direction and wind speed as a function of the underlying topography. The vectored firebreaks consist of linear features of a specified width that will interrupt fire spread: these features can be breached (if specified) under a given rule set.

Column	Name	Type	Description
1	grid_value	integer	Value in the FBP System fuel grid
2	export grid_value	integer	Value used when the FBP System fuel grid is exported
3	agency fuel type	string	Agency name for the FBP System fuel type
4	FBP fuel type	string	FBP System fuel used by Burn-P3
5	R	integer	Display colour red
6	G	integer	Display colour green
7	B	integer	Display colour blue
8	Hue	integer	Display hue
9	Sat	integer	Display saturation
10	Lum	integer	Display luminosity

Below is an example of a FBP System fuel lookup table:

```
grid_value, export grid_value, agency fuel type, FBP fuel type, R, G, B, hue, sat, lum
1,1,C-1 Spruce-Lichen Woodland,C-1,209,255,115,57,255,185
2,2,C-2 Boreal Spruce,C-2,34,102,51,95,128,68
3,3,C-3 Mature Jack or Lodgepole Pine,C-3,131,199,149,96,96,165
4,4,C-4 Immature Jack or Lodgepole Pine,C-4,112,168,0,57,255,84
5,5,C-5 Red and White Pine,C-5,223,184,230,206,122,207
11,11,D-1 Leafless Aspen,D-1,196,189,151,35,70,174
12,12,D-2 Green Aspen (with BUI Thresholding),D-2,137,112,68,27,86,103
13,13,D-1/D-2 Aspen,D-1/D-2,196,189,151,35,70,174
21,21,S-1 Jack or Lodgepole Pine Slash,S-1,251,190,185,3,227,218
22,22,S-2 White Spruce - Balsam Slash,S-2,247,104,161,-272,229,176
100,100,Not Available,Not Available,255,255,255,170,0,255
101,101,Non-fuel,Non-fuel,130,130,130,170,0,130
102,102,Water,Water,115,223,255,138,255,185
103,103,Unknown,Unknown,0,0,0,170,0,0
104,104,Unclassified,Unclassified,166,166,166,170,0,166
105,105,Vegetated Non-Fuel,Vegetated Non-Fuel,204,204,204,170,0,204
```

Figure 2.14 Fuel Lookup Chart used in Prometheus, Burn-P3 and Pandora
Sources: Natural Resources Canada, 2014; Parisien et al, 2005

The environment comprises the following variables: season, cause, duration of burning, and daily fire weather conditions. Season consists of time periods during the warm months when the daily fire weather conditions differ, as well as the state of the fuels whose phenology greatly affect fire behaviour (i.e., deciduous tree and graminoids). Cause is the type of fire ignition; causes and seasons can have distinct spatial ignition patterns. The duration of burning variable is the length of the burning period (in days) of each fire. This variable is weather-related and therefore reflects the rain-free period under which fires can achieve significant burning. The daily fire weather conditions variable represents the weather under which fire spread is simulated; that is, the weather attached to each spread-event day of a fire.

One time step represents one year and the simulation of this same year is repeated a very large number of times (hereafter, 'iterations'). Individual fires are modeled using a daily time step. The spatial extent is that of a study landscape (e.g., an ecoregion or land management unit), whereas the spatial resolution (i.e., pixel size) typically varies from 25 to 500 m. A buffer surrounding the study area should be added in order to avoid edge effect by letting fires ignite outside the study area and burn within its boundary.

Appendix E (Burn-P3 model design and process) provides information about the Burn-P3 design, process overview and scheduling.

2.5.5 Pandora

Pandora is a Windows application that gives users the ability to batch-run basic Prometheus simulations without using the Prometheus user interface. All the parameters for the simulations are specified in a single text file, including the locations of data input files such as fuels, terrain, and weather. Any number of simulations can be specified in the parameters text file. The input window, shown here, is optional and can be suppressed with a command line option (Canadian Forest Service, 2016).

Pandora is designed to run one or many Prometheus simulations without user intervention. It has been used primarily as a research tool, for such tasks as sensitivity analysis and ensemble modelling. It can also be called from other applications, which can then provide an alternative user interface for the Prometheus fire simulation engine.

The *PrometheusCOM* must be installed in order for Pandora to run. Note that the *PrometheusCOM* is only the engine and therefore not the same as the Prometheus application, which offers additional end-user functionality. Many of the advanced features of the Prometheus application are therefore not available in Pandora.

Simulation parameters are supplied to Pandora in a text file. For each simulation in the batch job, the text file specifies the necessary parameters including the locations of the input and output files. Shapefiles of the fire perimeters and grids of selected FBP components can be exported for each fire. The data input files are the same type and format as those used by Prometheus.

Pandora 3.4 is 64-bit and runs with Prometheus 5.5. Parameter file specifications have not changed since Pandora 3. Due to changes in the COM, this version of Pandora will not run with any pre-5.5 versions of Prometheus. Chances are it won't work with any post-5.5 versions either.

Appendix F (Pandora Input File Requirements) specifies the file input requirements for the Pandora application.

2.6 Summary

Wildfire plays a vital role in the conservation of biodiversity of various ecosystems. In order to facilitate planning, resource management in fire-prone ecosystems requires an understanding of wildfire behaviour and a viable approach to evaluating burn probability.

British Columbia has entered an era of increased frequency and severity of wildfires due to past fire suppression regimes and current climatological pressures which have contributed to the mountain pine beetle infestation. This has partially been addressed with temporary increases by BC's Ministry of Forests, Lands and Natural Resources Operations of Allowable Annual Cuts issued to Timber Supply Areas including the Morice and Lakes Timber Supply Areas as part of the Forest Management Strategy of the Nadia Forest District. This has only reduced but not taken away the substantial risks of catastrophic wildfires directly jeopardizing rural communities.

Continued research utilizing fire growth modelling and historic data assists in furthering our understanding of potential strategic interventions in the landscape that can effectively reduce such risks. Employing the functionality embedded in ArcGIS and Prometheus in combination with Pandora, as proposed in this research, enables the assessment and evaluation of various firebreak strategies in the Nadina Forest District.

The methodology used in this research for wildfire modelling and management evaluation of simulated firebreak management strategies is presented in Chapter 3 to follow.

3. Methodology

This chapter presents the research process, research methods and data selection and preparation steps applied as part of the model design. It is divided into 5 sections. Section 3.1 describes the research and simulation process and model design. Section 3.2 elaborates on the data selection process for the areas in scope. Data preparation steps are presented in section 3.3, followed by elaborations on model calibration and preparation in section 3.4. A chapter summary is given section 3.5.

3.1 Research Process and Model Design

This section outlines the research process for the simulation model of firebreak strategies for the Nechako sub-region of Southside. An overview of systems applications and process steps applied in the simulation of wildfires in this thesis is presented in Figure 3.1. The process steps used in this research project are shown in Figure 3.2. The sections specified in this figure correspond to the respective sections in this chapter.

The following subsections of this chapter provide details on the elements of the research process illustrated in Figure 3.1 and Figure 3.2. These subsections correspond to the components itemized in Figure 3.1 and Figure 3.2.

The process begins with data selection, encompassing source identification, cleaning (section 3.2). This includes the identification and selection of maps from databases on land use, land ownership, fuel types, topography and projection using ArcGIS. Once the data have been identified and selected, these are prepared (section 3.3) for analysis using *Mathwave Easyfit* in order to determine data trends, including probability density functions for wildfire count (section 3.3.1), -cause (section 3.3.2) and –size (section 3.3.3). Environmental and topographical data are prepared, including information on weather streams (section 3.3.4), elevation, slope and aspect (section 3.3.5). Finally, data are analysed to understand the relationship between distance to road and wildfire probability (section 3.3.6) and land use (section 3.3.7).

The resulting data are formatted for GIS presentation (using ArcGIS). With the data in place, the wildfire simulation model for the Southside is designed and applied under alternative scenarios and firebreak strategies over the planning period. This starts with the establishment of controllable variables (section 3.4.1), uncontrollable variables (section 3.4.2) and output indicators (section 3.4.3). The next steps in the model preparation and calibration process are the generation of a baseline ignition map (section 3.4.4), the allocation of fuel type to land use type (section 3.4.5) and the calibration of wildfire duration versus –size (section 3.4.6). Land use grids are then converted using ArcGIS ModelBuilder to represent each of the firebreak scenarios (section 3.4.7). The final preparatory steps in model preparation include the generation of an event list (section 3.4.8), the definition of simulation trial parameters (section 3.4.9) and the preparation of Pandora input files (section 3.4.10). The acquired results are then evaluated, enabling the preparation of recommendations on firebreak performance.

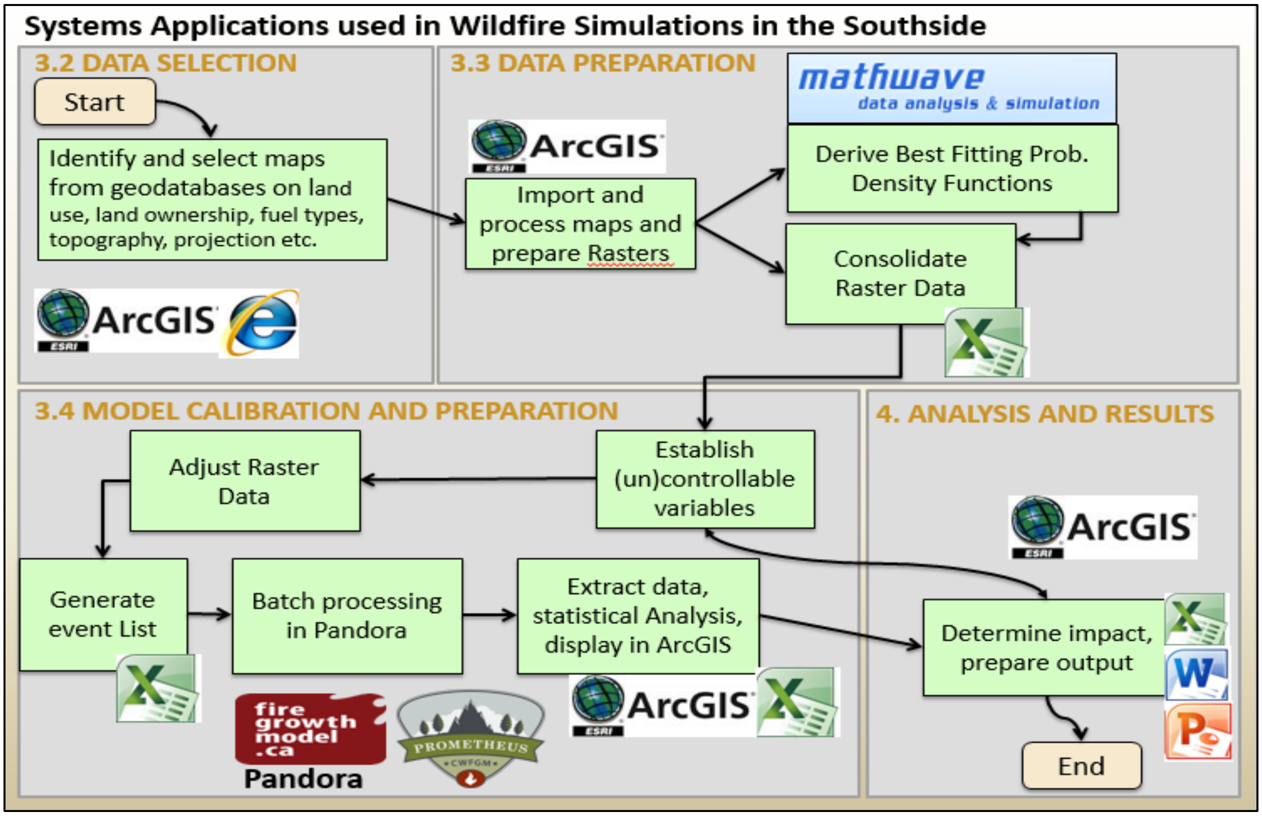


Figure 3.1 Systems applications and high level research process

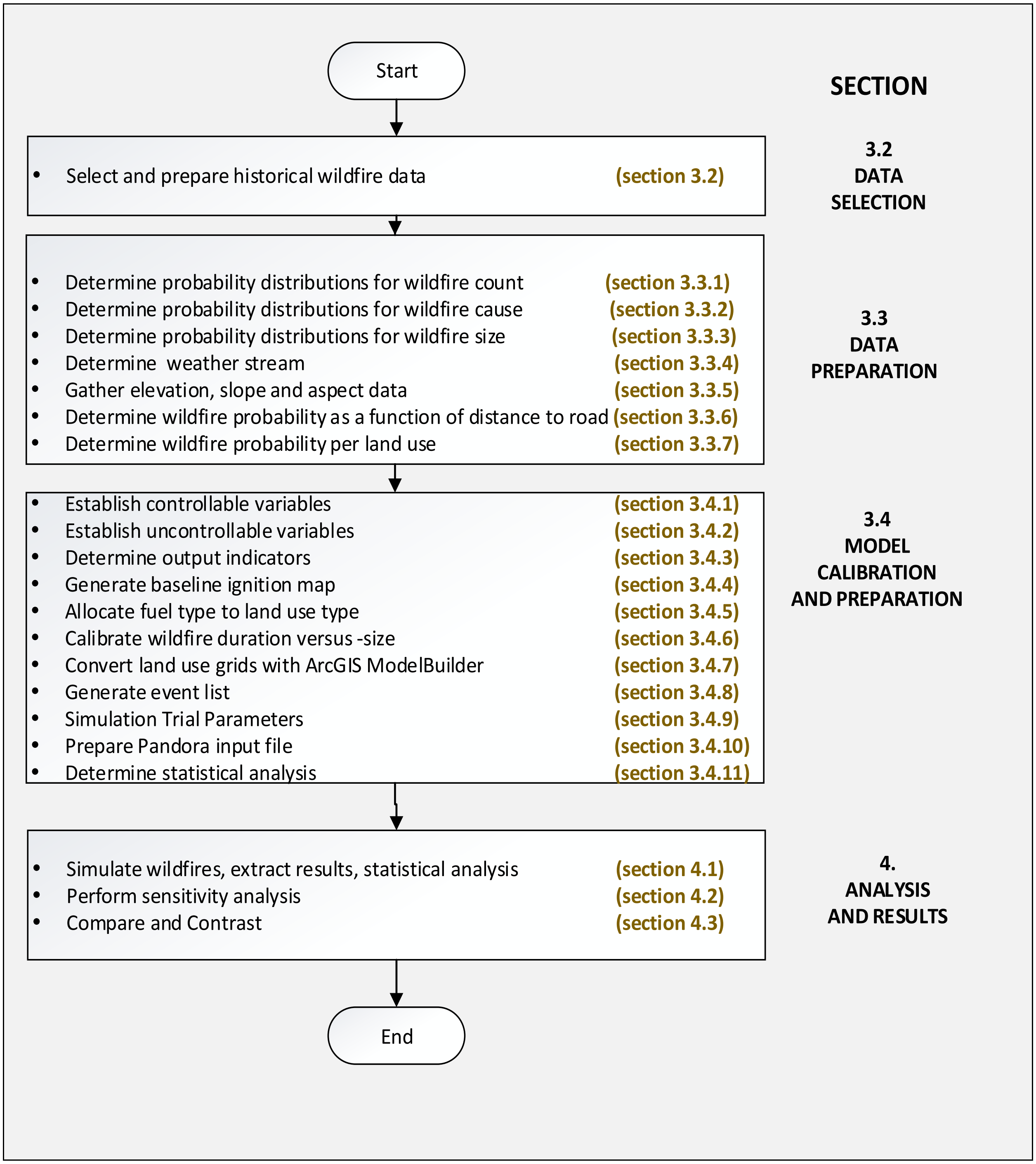


Figure 3.2 Research process flow
(sections refer to chapter sections)

3.2 Data selection

The Canadian National Fire Database (CNFDB) is a collection of forest fire locations and fire perimeters as provided by Canadian fire management agencies including provinces, territories, and Parks Canada (Burton et al., 2008, Parisien et al, 2006, Stocks et al, 2003, Amiro et al, 2001). To create the Canada-wide product, the data collected from each agency are projected into a common format and combined with data from other agencies. Attribute fields are standardized and agency specific attribute fields are removed. Polygon areas are calculated using GIS. The database is a large collaborative effort by all Canadian fire agencies. Compilation of the Canada-wide database was partially supported by the Canadian government programs of ENFOR (Energy from the Forest), the Program on Energy Research and Development, the Climate Change Action Fund, and Action Plan 2000 (Canadian Forest Service, 2013).

Data from the Canadian Wildland Fire Information System were extracted and the polygon data (large fire data) were converted to rasters each representing 1-year of data on the timing and location of large fires. A raster consists of a matrix of cells (or pixels) organized into rows and columns where each cell contains a value representing information. For example, a raster can represent digital aerial photographs, imagery from satellites, digital pictures, or scanned maps (ESRI, 2008).

Table 3.1 lists the sources of the data sets of the Nechako Lakes Electoral District used in this study. The national fire database has been used as a historical reference deriving the predictive factors to be applied in the simulation modelling cycles of the wildfire model described below. The main criterion in the data selection process is that the data must reflect ecological and/or community elements that are either affected by, or controlled in various adaptive strategies in the scope for this research. Some data can be used for predictive purposes using methods such as logistic regression and 'weights of evidence' as in the Spatial Data Modeller of ArcGIS. These elements include water bodies, land use data, cadastral information, elevation, climatological data and topography. Data were obtained from various public sources as indicated in Table 3.1. Spatial layers in these maps were available as Environmental Systems Research Institute (ESRI) Shapefile, point files and rasters to support detailed analyses and geo-referenced mapping. They enable geo-statistical analysis and modelling using various spatial toolsets available as part of the ESRI-software.

Based on wildfire locations, point and polygon data files were merged and then clipped to fit within the Nechako Lakes Electoral District. This resulted in 127 duplicate records referenced in both the point- and polygon files. Duplicates were identified through their Fire ID number. Duplicate, overlapping records existing in both the point- and polygon database were then removed to cleanse the dataset prior to analysis. Pre-selection left a total of 1517 unique CNFDB records in the Nechako Lakes Electoral District from 1950 to 2012. Data records before 1950 and after 2012 were occasionally reported to be incomplete and it was therefore decided to truncate these from our dataset (Canadian Forest Service, 2013).

After removal of a number of duplicates and truncating fires from before 1950 and after 2012, the sub-set of these data from the National Fire Database covering the Nechako Lakes Electoral District included 1376 fires from the large fire Shapefile, and 1460 fires from the small fires Shapefile. These data were used as input to derive probability density functions as described in section 3.3 below.

Table 3.1 Datasets Sources for the Nechako Lakes Electoral District used for this study

Dataset	Attribute	File name	Source
National Fire Database: Large Fires	Shapefile	NFDB_poly_20140210.shp	http://cwfis.cfs.nrcan.gc.ca
National Fire Database: Small fires	Point file	NFDB_point_20131108.shp	http://cwfis.cfs.nrcan.gc.ca
Ecozones in Canada	Shapefile	Ecozones.shp	http://esri.ca/en/content/ecozones-canada
Nechako Lakes Electoral District	Shapefile	NEC_Areal.shp and BC_Electoral_Districts.shp	http://www.bcstats.gov.bc.ca
Towns in the Nechako Lakes Electoral District	Shapefile	NEC_SVA.shp	http://www.bcstats.gov.bc.ca
Land use data	Shapefile	BTM_PLU_V1_polygon	http://www.data.gov.bc.ca
Broadleaf Cover (optional)	Shapefile	NRCBRDLFFR_polygon	http://www.geobase.ca/
Land Ownership Data	Shapefile	F_OWN_polygon	http://www.data.gov.bc.ca
Elevation	Raster	Various DEM files in block 93e, 93f, 93k and 93l	http://www.geobase.ca/ http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/3A537B2D-7058-FCED-8D0B-76452EC9D01F.html
Road Network	Shapefile	NRN_BC_11_0_ROADSEG.shp	http://geogratis.gc.ca

Figure 3.3 provides a visual representation of wildfire occurrence in and around the Nechako Lakes Electoral District from 1950-2012. The data in Figure 3.4 display a visual close-up of the same data used in Figure 3.3 but restricted to the Southside. Both figures illustrate the randomness of wildfires across the region. This visual presentation illustrates where wildfires have occurred in the given time period, but does not provide additional insight into possible underlying temporal and spatial patterns and relationships. For this reason, the underlying data are broken down further in the following for further analysis.

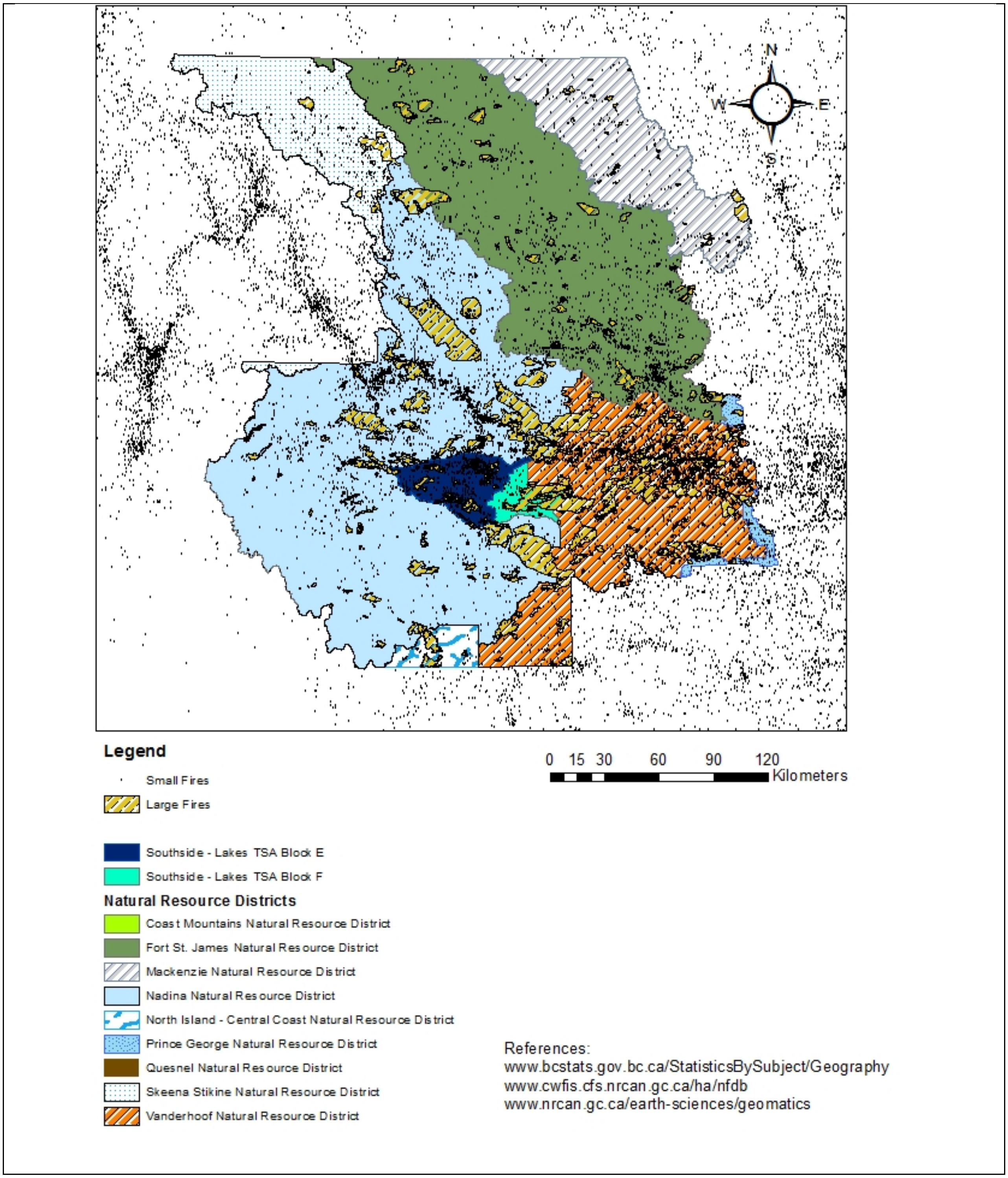


Figure 3.3 Wildfire occurrence (1950-2012) in the Nechako Lakes Electoral District
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

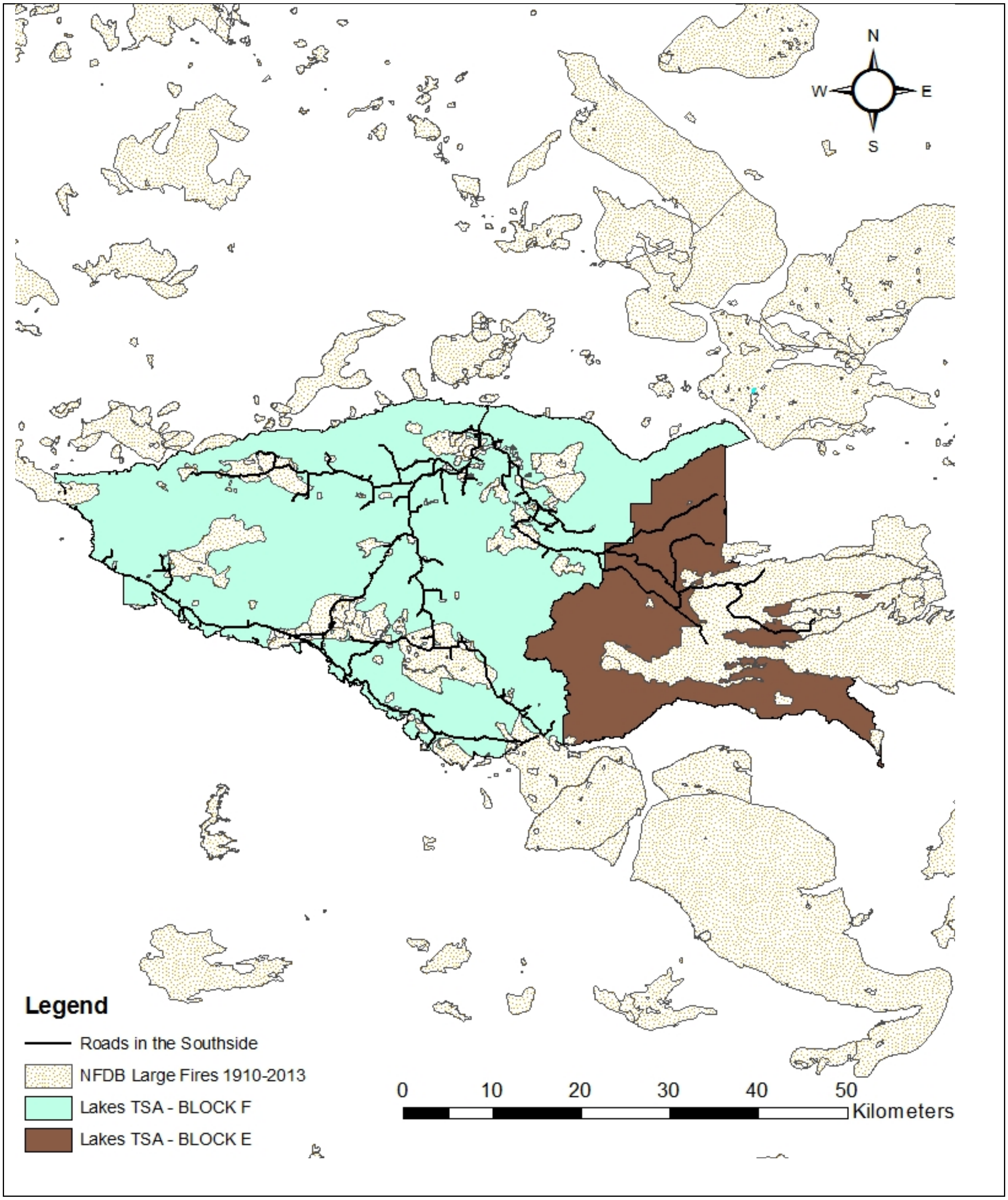


Figure 3.4 Wildfire occurrence (1910-2013) in and around the Southside
Source: Canadian Forest Service, 2013

Table 3.2 provides a summary of the annual wildfire count during the period from 1950 to 2012 by cause of the fire. In the selected dataset, all causes were known. Over the entire period, 74.7% of the wildfires were recorded to have a human cause, and the remaining 25.3% were caused by lightning. The recorded period after 2000 showed the highest percentage of wildfires as compared to the other decades. This could be caused by a temporary peak in available biofuel as a result of dead biomass from the wave of pine beetle attacks in the region, and the change in fire management strategies (BCMOFR, 2009; Filmon, 2003; Hirsch et al, 2004; Vojtek, 2007). The data do not show any other evident visible trend in the percentage throughout the period.

Table 3.2 Annual wildfire count from 1950-2012 by cause, Nechako Lakes Electoral District

Table 1. Annual wildfire count in the period 1950-2012 by cause
Nechako Lakes District, B.C., Canada

period ▼	Total	Average annual count and % of fires per cause				Average nr. fires per year
		Human H	%	Lightning L	%	
1950-1959	190	142	74.7%	48	25.3%	19
1960-1969	214	150	70.1%	64	29.9%	21
1970-1979	182	162	89.0%	20	11.0%	18
1980-1989	374	331	88.5%	43	11.5%	37
1990-1999	229	184	80.3%	45	19.7%	23
2000-2009	232	117	50.4%	115	49.6%	23
2010-2012	96	47	49.0%	49	51.0%	32
OVERALL	**1517**	**1133**	74.7%	**384**	25.3%	**24**

Source: Canadian Forest Service, 2013

Table 3.3 shows the monthly number of wildfires from 1950-2012 by decade. Table 3.4 displays these figures as percentages. Overall, the five months between October 1 and March 31 only account for 1.09% of the total number of wildfires, while the six months between April 1 and September 30 accounted for 93.21% of the total. October showed a relatively low number of wildfires, representing only 5.7% of the total. The annual average number of wildfires has increased gradually over the decades. While there were 20 fires per year on average between 1950 and 1979, there were 28 fires per year on average between 1980 and 2009 (Table 3.3).

Table 3.3 Monthly wildfire count from 1950-2012 by decade, Nechako Lakes Electoral District

Month ▼		Wildfire count (number) by period and month							
		1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2012	1950-2012
Jan	1	0	0	0	1	1	0	0	2
Feb	2	0	0	0	0	0	0	0	0
Mar	3	1	3	0	1	2	0	0	7
Apr	4	25	17	5	69	45	48	17	226
May	5	87	76	47	56	46	59	7	378
Jun	6	24	22	23	34	15	38	4	160
Jul	7	26	35	25	29	15	54	34	218
Aug	8	18	45	24	41	35	22	21	206
Sep	9	5	16	53	88	54	7	3	226
Oct	10	0	0	4	54	16	3	10	87
Nov	11	0	0	1	1	0	1	0	3
Dec	12	4	0	0	0	0	0	0	4
Total		**190**	**214**	**182**	**374**	**229**	**232**	**96**	**1517**
Annual average		**20**			**28**			**32**	**1517**
Overall		**1517**							

Source: Canadian Forest Service, 2013

Table 3.4 Monthly wildfire count (%) from 1950-2012 by decade, Nechako Lakes Electoral District

Month ▼		Wildfire count (%) by period and month								
		1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2012	1950-2012	SHARE
Jan	1	0.0%	0.0%	0.0%	0.3%	0.4%	0.0%	0.0%	0.1%	0.59%
Feb	2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
Mar	3	0.5%	1.4%	0.0%	0.3%	0.9%	0.0%	0.0%	0.5%	
Apr	4	13.2%	7.9%	2.7%	18.4%	19.7%	20.7%	17.7%	14.9%	93.21%
May	5	45.8%	35.5%	25.8%	15.0%	20.1%	25.4%	7.3%	24.9%	
Jun	6	12.6%	10.3%	12.6%	9.1%	6.6%	16.4%	4.2%	10.5%	
Jul	7	13.7%	16.4%	13.7%	7.8%	6.6%	23.3%	35.4%	14.4%	
Aug	8	9.5%	21.0%	13.2%	11.0%	15.3%	9.5%	21.9%	13.6%	
Sep	9	2.6%	7.5%	29.1%	23.5%	23.6%	3.0%	3.1%	14.9%	
Oct	10	0.0%	0.0%	2.2%	14.4%	7.0%	1.3%	10.4%	5.7%	5.7%
Nov	11	0.0%	0.0%	0.5%	0.3%	0.0%	0.4%	0.0%	0.2%	0.5%
Dec	12	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	
Total		**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Canadian Forest Service, 2013

Summaries of monthly wildfire size (ha) from 1950-2012 by decade are provided in Table 3.5 (total) and Table 3.6 (%). Table 3.7 displays these data in terms of their share in the total impact. It is shown that from a size-perspective, October 1 through March 31 only account for 0.54% of the total wildfire area burned, while the balance (99.46%) is burned from April 1 through September 30. The annual average area burned has increased throughout the decades. While the average area burned was 3477 hectares in the Nechako Lakes Electoral District between 1950 and 1979, it had increased to 3891 between 1980 and 2009, and showed a dramatic increase in the three years from 2010 to 2012.

Table 3.5 Monthly wildfire size (ha) from 1950-2012 by decade, Nechako Lakes El. Distr.

Month		Burned area (ha) by decade and month								
▼		1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2012	1950-2012	SUM
Jan	1	0	0	0	2	4	0	0	6	6
Feb	2	0	0	0	0	0	0	0	0	0
Mar	3	8	78	0	4	3	0	0	93	93
Apr	4	796	508	27	527	321	664	283	3126	3126
May	5	11322	3143	1030	22882	619	49688	27	88711	88711
Jun	6	5336	1300	214	2361	431	15111	6103	30856	30856
Jul	7	28348	10412	1834	3915	1032	9981	76808	132330	132330
Aug	8	10529	23300	1182	2228	466	2336	13676	53716	53716
Sep	9	391	1442	2825	2010	1030	79	42	7818	7818
Oct	10	0	0	145	876	125	33	279	1458	1458
Nov	11	0	0	64	8	0	11	0	83	83
Dec	12	77	0	0	0	0	0	0	77	77
Total		56806	40182	7321	34813	4031	77901	97218	318271	318271
Annual average		3477			3891			32406		
Overall		318271								

Source: Canadian Forest Service, 2013

Table 3.6 Monthly wildfire size (%) from 1950-2012 by decade, Nechako Lakes El. Distr.

Month		Percentage (%)of total burned area (ha) by period and month								
▼		1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2012	1950-2012	%
Jan	1	0.00%	0.00%	0.00%	0.01%	0.09%	0.00%	0.00%	0.00%	
Feb	2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%
Mar	3	0.01%	0.19%	0.00%	0.01%	0.07%	0.00%	0.00%	0.03%	
Apr	4	1.40%	1.26%	0.37%	1.51%	7.96%	0.85%	0.29%	0.98%	
May	5	19.93%	7.82%	14.06%	65.73%	15.35%	63.78%	0.03%	27.87%	
Jun	6	9.39%	3.24%	2.93%	6.78%	10.69%	19.40%	6.28%	9.69%	
Jul	7	49.90%	25.91%	25.05%	11.25%	25.59%	12.81%	79.01%	41.58%	99.46%
Aug	8	18.53%	57.99%	16.15%	6.40%	11.56%	3.00%	14.07%	16.88%	
Sep	9	0.69%	3.59%	38.59%	5.77%	25.56%	0.10%	0.04%	2.46%	
Oct	10	0.00%	0.00%	1.98%	2.52%	3.11%	0.04%	0.29%	0.46%	
Nov	11	0.00%	0.00%	0.88%	0.02%	0.00%	0.01%	0.00%	0.03%	0.51%
Dec	12	0.14%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	
Total		100%	100%	100%	100%	100%	100%	100%	100%	100%

Source: Canadian Forest Service, 2013

Table 3.7 Monthly wildfire count and size (ha) from 1950-2012, Nechako Lakes El. Distr.

Wildfire figures: periodicity, cause, count and impact, Nechako Lakes District, B.C., Canada								
Month		Number of fires in the period 1950-2012				Total area (ha) burned in the period 19		
▼	▼	▼		%	SHARE	ha	%	SHARE
Jan	1	2	9	0.1%	0.59%	6	0.00%	0.03%
Feb	2	0		0.0%		0	0.00%	
Mar	3	7		0.5%		93	0.03%	
Apr	4	226	788	14.9%	93.21%	3126	0.98%	99.46%
May	5	378		24.9%		88711	27.87%	
Jun	6	160		10.5%		30856	9.69%	
Jul	7	218		14.4%		132330	41.58%	
Aug	8	206		13.6%		53716	16.88%	
Sep	9	226		14.9%		7818	2.46%	
Oct	10	87	94	5.7%	6.2%	1458	0.46%	0.51%
Nov	11	3		0.2%		83	0.03%	
Dec	12	4		0.3%		77	0.02%	
Total		1517	891	100%	100%	318271	100%	100%

Source: Canadian Forest Service, 2013

Table 3.8 shows the monthly wildfire count and burned area from 1950-2012 by cause. Table 3.9 shows the breakdown per cause. Nearly 100% of wildfires in April, May and September were caused by human activity, with 98.8% and 99.9% of the total wildfire area in respectively April and September. Lightning activity generally peaked during July and August, causing respectively 78.4% and 66.0% of all fires in these periods. Due to the relative larger size of wildfires caused by lightning, this resulted in an ever larger percentage of area burned by this cause (98.4% in July and 83.2% in August). In terms of impact measured by area burned, due to the relatively larger wildfire sizes when caused by lightning, these fires contribute to the largest portion of the total area in all months except for April and September.

Table 3.8 Monthly wildfire count and burned area 1950-2012 by cause, Nechako Lakes El. Distr.

Month		Number of fires 1950-2012 by cause				Burnt area (ha) 1950-2012 by cause				
▼	▼	Human	Lightning	% Human	% lightning	Human	Lightning	total	Human %	Lightning %
Jan	1	2	0	100.0%	0.0%	5.8	0	5.8	100.00%	0.00%
Feb	2	0	0	N.A.	N.A.	0	0	0	N.A.	N.A.
Mar	3	7	0	100.0%	0.0%	92.7	0	92.7	100.00%	0.00%
Apr	4	224	2	99.1%	0.9%	3087.1	38.7	3125.8	98.76%	1.24%
May	5	364	14	96.3%	3.7%	39832	48878.5	88710.5	44.90%	55.10%
Jun	6	106	54	66.3%	33.8%	10956.7	19898.8	30855.5	35.51%	64.49%
Jul	7	47	171	21.6%	78.4%	2096.5	130233.1	132329.6	1.58%	98.42%
Aug	8	70	136	34.0%	66.0%	9029.81	44686	53715.81	16.81%	83.19%
Sep	9	223	3	98.7%	1.3%	7807.5	10.9	7818.4	99.86%	0.14%
Oct	10	87	0	100.0%	0.0%	1457.81	0	1457.81	100.00%	0.00%
Nov	11	3	0	100.0%	0.0%	82.6	0	82.6	100.00%	0.00%
Dec	12	0	4	0.0%	100.0%	0	76.7	76.7	0.00%	100.00%
Total		**1133**	**384**	74.2%	25.8%	**74449**	**243823**	**318271**	63.4%	36.6%

Source: Canadian Forest Service, 2013

Given the relative insignificance of the numbers of wildfires from October 1 through March 31 in view of our research goals, only the period from April 1 through September 30 will be considered in this research. As displayed in Table 3.9, when omitting the 103 historic records outside this period, this leaves 1414 records for further analysis.

Table 3.9 Wildfire data 1950-2012 by season, Nechako Lakes El. Distr.

SEASON	From-to	Number of fires			Percentage of fires		
		Human	Lightning	Total	Human	Lightning	Total
LOW	Oct-Mar	99	4	103	96.12%	3.88%	100.00%
HIGH	Apr-Sep	1034	380	1414	73.13%	26.87%	100.00%
ALL YEAR		1133	384	1517	74.69%	25.31%	100.00%
SEASON	% size	Size (km2)			Size (%)		
	in season	H	L	TOT	H	L	TOT
LOW	0.54%	16.39	0.77	17.16	95.5%	4.5%	100.0%
HIGH	99.46%	728.10	2437.46	3165.56	23.0%	77.0%	100.0%
ALL YEAR	100.00%	744.49	2438.23	3182.71	59.3%	40.74%	

Source: Canadian Forest Service, 2013

A further look at the distribution of wildfire count by size and cause from 1950-2012 reveals that while wildfires of sizes up to 100 hectares represent 89.3% of the total number of fires, they only represent 5% of the total impact, as shown in Figure 3.5 and Table 3.10. Based on these findings, it was decided to only include wildfires greater than or equal to 100 hectares for the derivation of probability density functions.

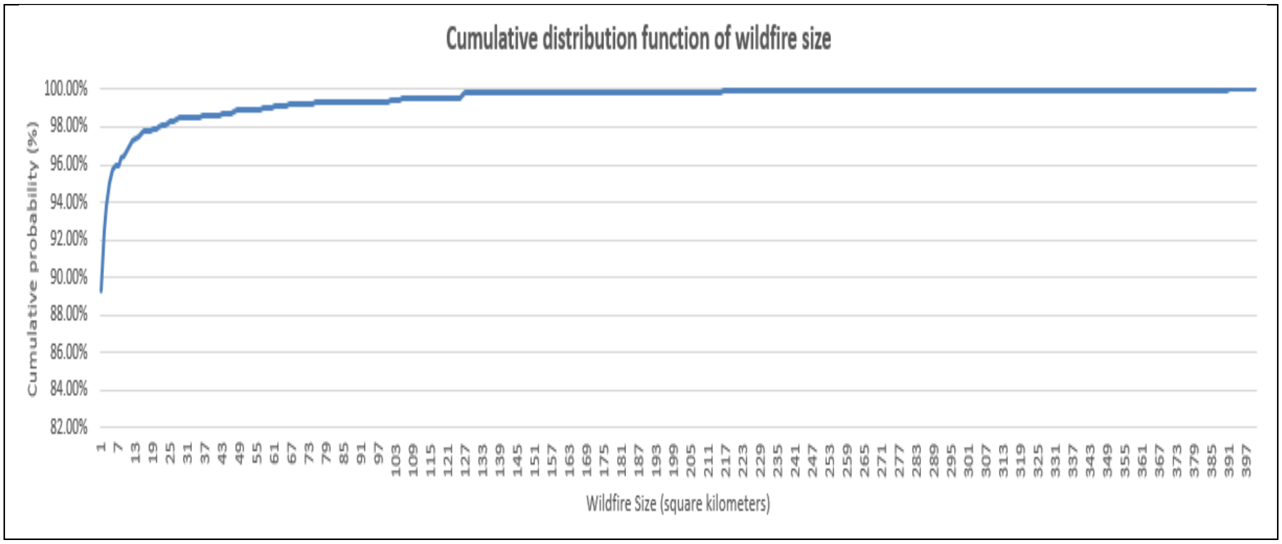


Figure 3.5 Cumulative distribution function of wildfire sizes of >= 100 hectares

Table 3.10 Wildfire count and impact (1950-2012) by size and cause, Nechako Lakes El. Distr.

Distribution of wildfire count in the period 1950-2012 by size and cause									
Size	Absolute count			Absolute percentage			Cumulative count		
(hectares)	Human	Lightning	Total	Human	Lighting	Total	Human	Lighting	Total
0-100	1061	293	1354	93.6%	76.3%	89.3%	1061	293	1354
100-10000	71	82	153	6.3%	21.4%	10.1%	71	82	153
0-10000	1132	375	1507	99.9%	97.7%	99.3%	1132	375	1507
10000-20000	0	8	8	0.0%	2.1%	0.5%	1132	383	1515
20000-30000	1	0	1	0.1%	0.0%	0.1%	1133	383	1516
30000-40000	0	1	1	0.0%	0.3%	0.1%	1133	384	1517
Total (0-40000 ha)	1133	384	1517	100.0%	100.0%	100.0%	1133	384	1517
Total (100-40000 ha)	72	91	163	6.4%	23.7%	10.7%	72	91	163

Impact of wildfires in the period 1950-2012 by size and cause									
Size	Absolute impact (burned ha			Absolute percentage			Cumulative impact		
(hectares)	Human	Lightning	Total	Human	Lighting	Total	Human	Lighting	Total
0-100	12426	3566	15992	16.7%	1.5%	5.0%	12426	3566	15992
100-10000	40446	107362	147808	54.3%	44.0%	46.4%	40446	107362	147808
0-10000	52872	110928	163799	71.0%	45.5%	51.5%	52872	110928	163799
10000-20000	0	93822	93822	0.0%	38.5%	29.5%	52872	204750	257621
20000-30000	21577	0	21577	29.0%	0.0%	6.8%	74449	204750	279198
30000-40000	0	39073	39073	0.0%	16.0%	12.3%	74449	243823	318271
Total	74449	243823	318271	100.0%	100.0%	100.0%	74449	243823	318271
Total (100-40000 ha)	62023	240257	302279	83.3%	98.5%	95.0%	62023	240257	302279

Source: Canadian Forest Service, 2013

3.3 Data Preparation

3.3.1 Probability density function of wildfire count

The probability density function parameters for wildfire count of fires of at least 100 hectares from April through September in the Nechako Lakes Electoral District were determined based on the actual history from 1950-2012, by deriving the overall performance when comparing the sum of rankings for best fit based on the Kolmogorov-Smirnov Test, the Anderson Darling test and the Chi Square Test as determined by *Mathwave Easyfit*.

Table 3.11 shows the parameters of best-fit probability densities for the parameter 'wildfire count,' using the software application *Mathwave Easyfit* to produce the parameter estimates. Based on these criteria for each of the six months considered, the best overall fit was given with the Poisson probability density function. The lambda value of the Poisson distribution function for the Southside was derived by its surface in proportion to the surface of the Nechako Lakes Electoral District. The Poisson probability density function is a discrete distribution with memoryless properties. It has been used successfully elsewhere to describe fire starts (Green, 1989; Harrington and Donnelly, 1978).

Table 3.11 Probability density function parameters wildfire count, Nechako Lakes El. Distr.

Probability Density Function Parameters for Wildfire Count								
MONTH	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Surface**	
Best Fit	Poisson	Poisson	Poisson	Poisson	Poisson	Poisson	**(km^2)**	**%**
Data Domain	Discrete	Discrete	Discrete	Discrete	Discrete	Discrete		
λ_N *)	0.07937	0.47619	0.31746	0.84127	0.58730	0.25397	73795	100.00%
λ_{SS} **)	0.00255	0.01528	0.01019	0.02700	0.01885	0.00815	2368	3.21%
Legend	*) Poisson lambda parameter estimates for the Nechako Lakes Electoral District based on Mathwave Easyfit best fit results							
	**) Poisson lambda parameter estimates for the Southside based on Mathwave Easyfit best fit results							

Source: Canadian Forest Service, 2013

Details on the application of the data fit to wildfire counts are found in Appendix G. 'Discrete Probability Density Function: Poisson'

Figure 3.6 graphically displays the probability density functions for monthly parameters (April through September) for all data including human and lightning causes combined, for the Nechako Lakes Electoral District, based on the Poisson probability density function $f(x) = \frac{\lambda^x e^{-\lambda}}{x!}$ with single parameter lambda. For example, the probability of one wildfire to occur in April given by this function is 0.0733 while the probability of 2 fires in April by the same function is 0.0014. The highest lambda value for this function occurs in July when the probability of one single wildfire fire is 0.37.

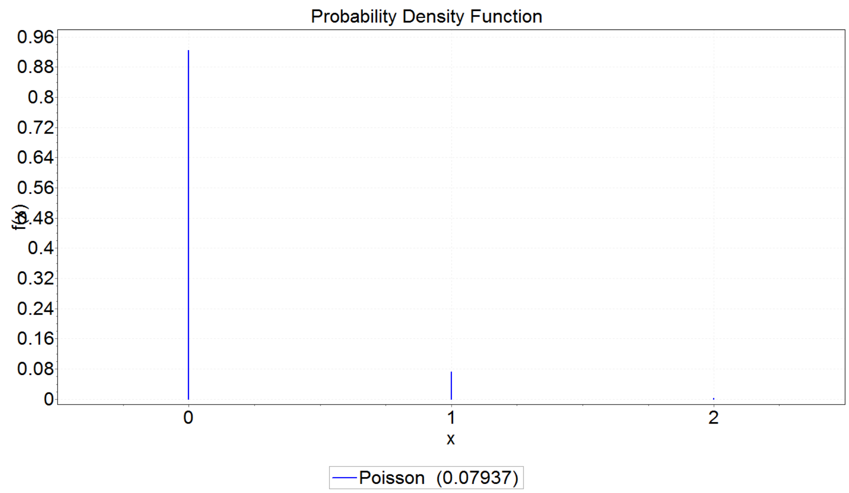
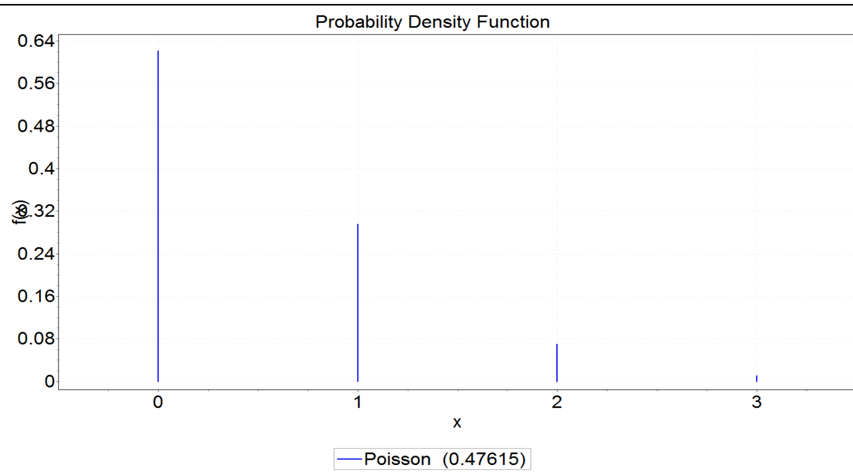
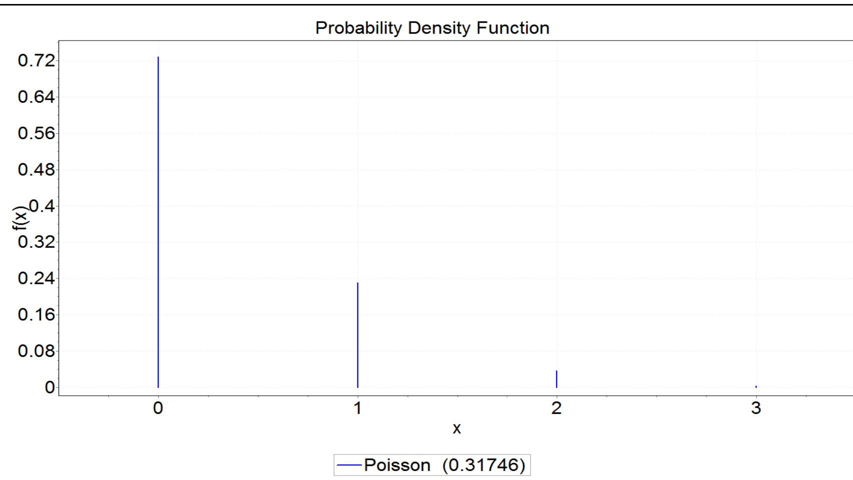
Month	Lambda	Distribution function
Apr	0.07937	
May	0.47615	
Jun	0.31746	

Figure 3.6 Wildfire count prob. density function (1950-2012), Nechako Lakes El. Distr

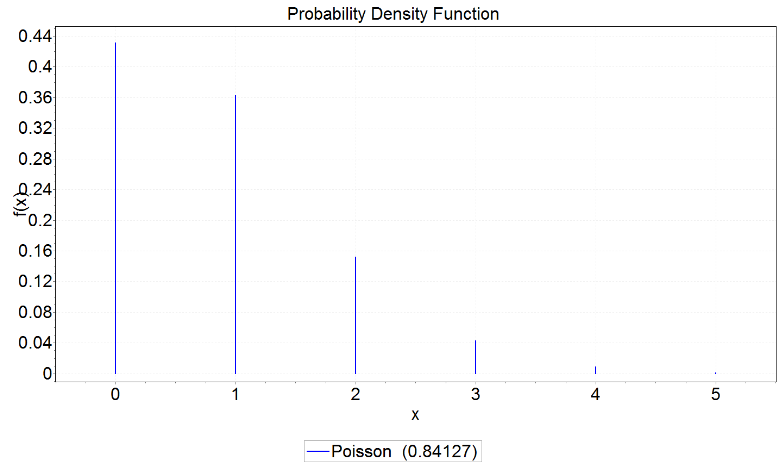
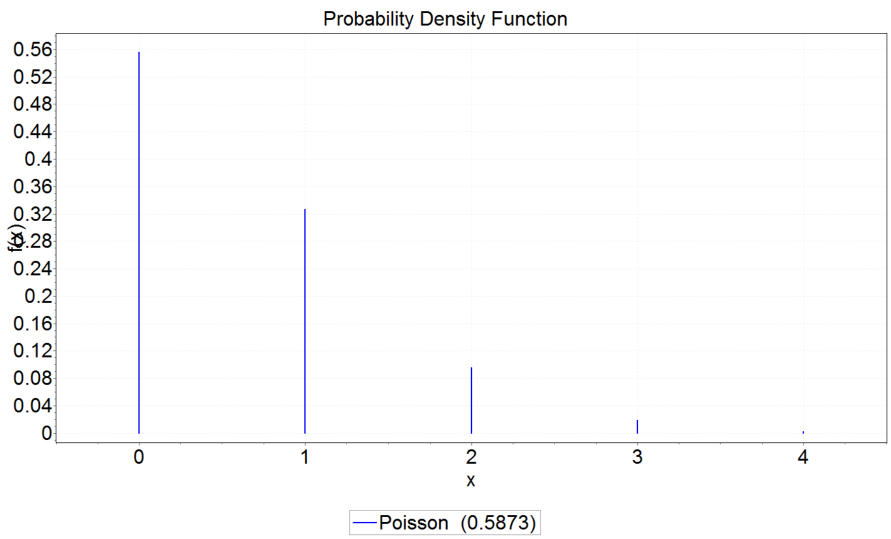
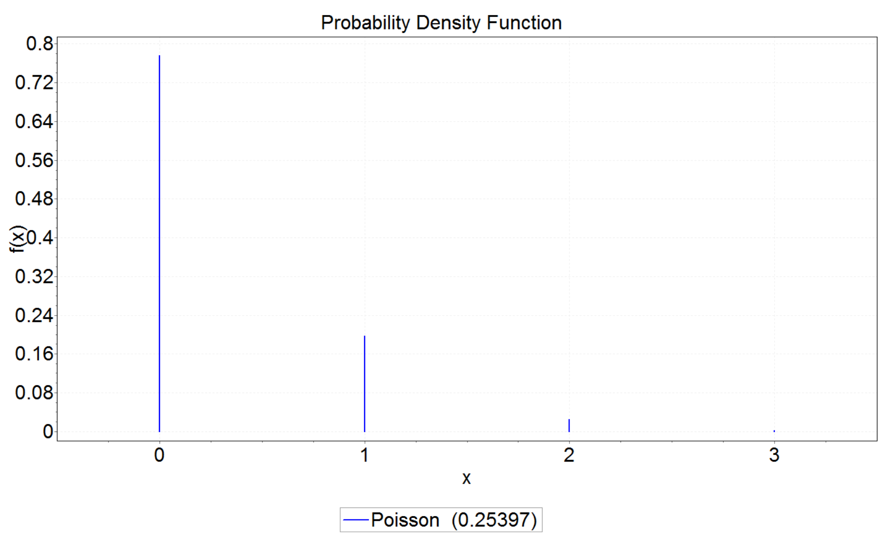
Source: Canadian Forest Service, 2013		
Jul	0.84127	
Aug	0.58730	
Sep	0.25397	

Figure 3.6 Wildfire count prob. density function (1950-2012), Nechako Lakes El. Distr
Source: Canadian Forest Service, 2013

3.3.2 Probability density function of ignition cause

Based on historic data of wildfires over 100 hectares from April through September from the Nechako Lakes Electoral District over the period from 1950 to 2012, distinct patterns occur throughout the six months from April through September. Figure 3.7 shows that in April and September, all wildfires were caused by human activity throughout the entire period. In June, July and August, the majority of fires was caused by lightning, with a peak in July when 88.7% of all wildfires in the Nechako Lakes Electoral District were caused by lightning. Please note that Figure 3.7 displays averages. For each month, the maximum probability between 1950 and 2012 for either cause was 100% which is to say that for each of the 6 months displayed there has been at least 1 month throughout the entire 63-year period in which only one of the two causes occurred.

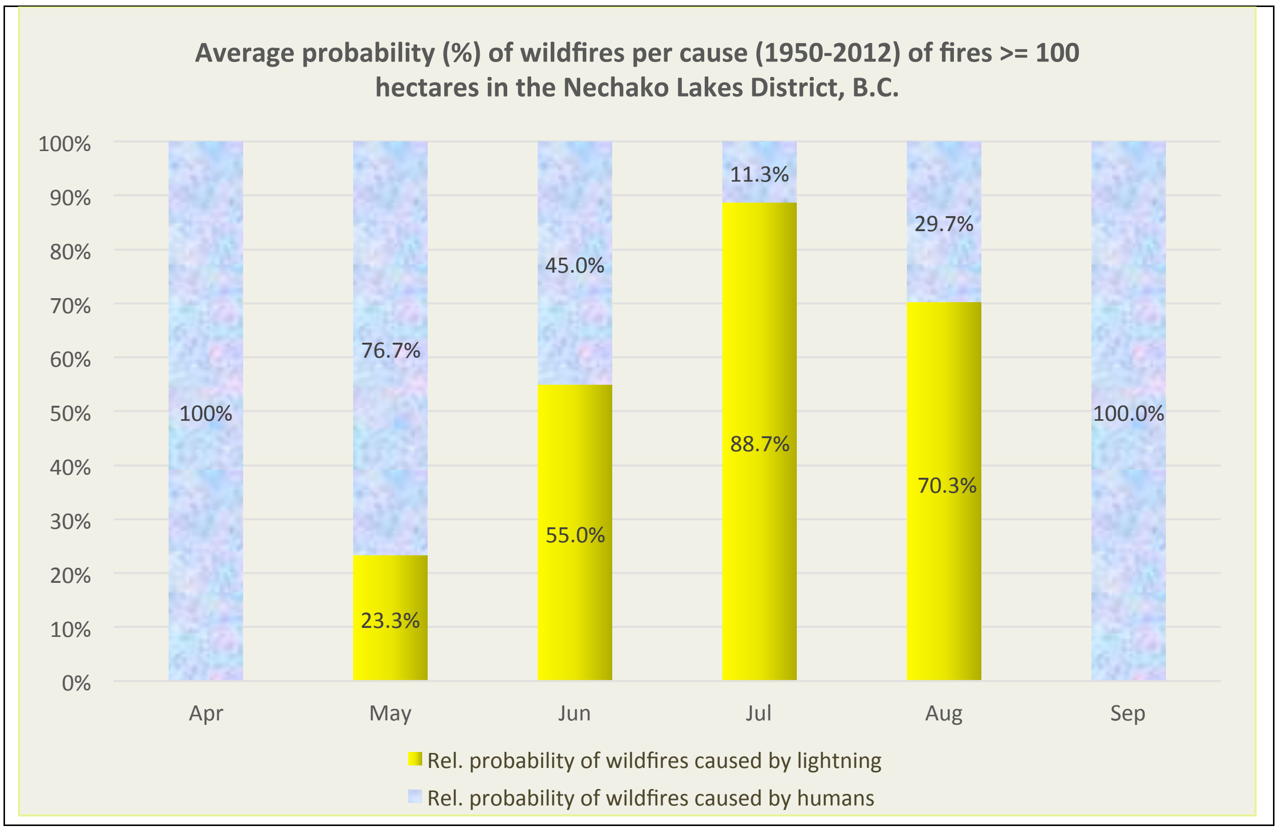


Figure 3.7 Average relative probability per cause of wildfires >= 100 ha, Nechako Lakes.
Source: Canadian Forest Service, 2013

3.3.3 Probability density function of wildfire size

Three distinct probability density functions were applied using *Mathwave Easyfit* to compare data fits for the parameters of 'wildfire size'. The best fit was determined using the Kolmogorov-Smirnov Test, the Anderson Darling test and the Chi Square Test. The best overall fit was determined by identifying the lowest sum of rankings from these three tests using *Mathwave Easyfit*. Table 3.12 shows the parameters of best-fit probability densities for the parameter 'wildfire size,' using *Mathwave Easyfit* to produce the parameter estimates. For April and September, insufficient historic data were available to provide a best fit using *Mathwave Easyfit* for the case of fires caused by lightening.

When selecting the overall best fit to our data, the ideal scenario would be that only one function would cover all data. The principle of parsimony is often applied in statistics to ensure that the minimum amount of parameters is used to accurately describe a phenomenon. When using *Mathwave Easyfit*, the results are ranked and it is then up to the user to decide which density function should be used based on the criteria applied. If an underlying dynamic for wildfire size exists, using only one single density function with varying parameter values would logically make sense. However, the historic data on wildfire size used for this research show a high variability in terms of the ranking of density functions.

The probability density functions for fire size (at least 100 ha) are described by a continous probability density function with random variables in units of hectares. *Mathwave Easyfit* is used to identify several representative best fitting functions including: log Pearson 3 (months of April and July), inverse Gaussian (September – human caused), Pearson 5 (June and August – human caused), Frechet 3P (May – human), Wakeby (May – lightning), Fatique life (June – lightning), and lognormal (August – lightning). Figure 3.8 and Figure 3.9 display the cumulative distribution functions for the Table 3.12 parameter sets for all wildfires caused respectively by humans (3.9) and by lightning (3.10).

Appendix H 'General Extreme Events' specifies the decision logic, parameters and mathematical equations for each of the best fitting distribution functions identified in Table 3.12 and in Figures 3.8 and 3.9 below.

Table 3.12 Probability density functions for wildfire sizes >= 100 ha, Nechako Lakes El. Distr.

CAUSE	MONTH	Apr	May	Jun	Jul	Aug	Sep	Total
HUMAN	Best Fit	Log-Pearson 3	Frechet 3P	Pearson 5 (3P)	Log-Pearson 3	Pearson 5 (3P)	Inv. Gaussian (3P)	
	Data Domain	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	
	Total # fires > 100 ha (63 yrs)	5	23	9	6	11	16	70
	α	2.1752	0.62891	0.82829	10.415	0.9039		
	β	0.25028	87.144	147.71	0.21413	112.48		
	γ	4.5433	97.134	73.063	3.095	96.231	88.807	
	μ						232.39	
	λ						76.017	
LIGHTNING	Best Fit	N.A.	Wakeby	Fatigue Life (3P)	Log-Pearson 3	Lognormal (3P)	N.A.	
	Data Domain	N.A.	Continuous	Continuous	Continuous	Continuous	N.A.	
	Total # fires > 100 ha (63 yrs)	0	7	11	47	26	0	91
	α		32355	2.5451	11.1			
	β		1.5908	372.51	0.42885			
	γ		0	136.28	2.0145	101.37		
	δ		0					
	k							
	σ					2.0016		
	ζ		-5536.4					
	λ							
	μ					5.9122		
TOTAL	Total # fires > 100 ha (63 yrs)							161

Source: Canadian Forest Service, 2013

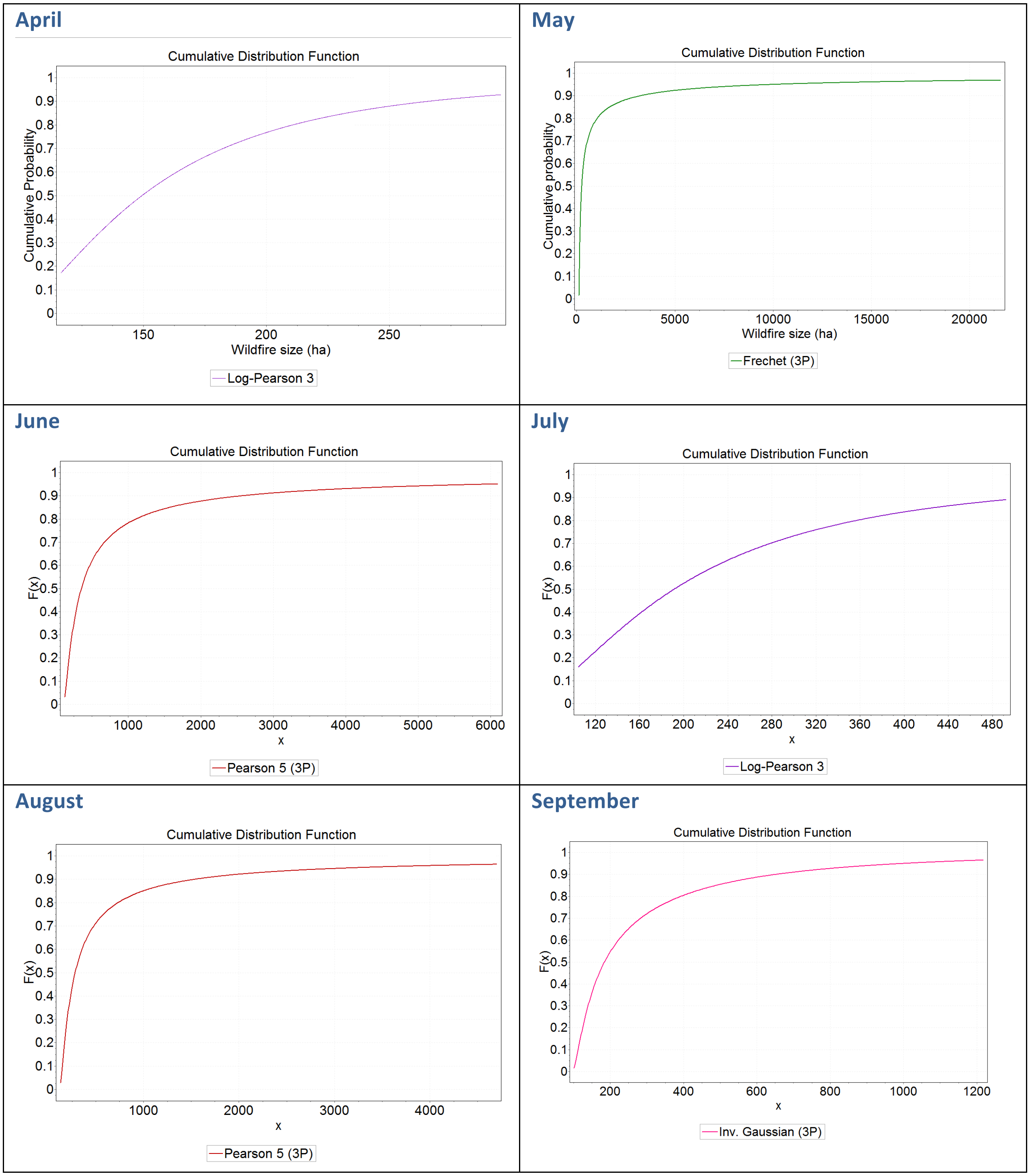


Figure 3.8 Cum. Distr. Function of wildfire sizes >= 100 ha with human cause.
Source: Canadian Forest Service, 2013

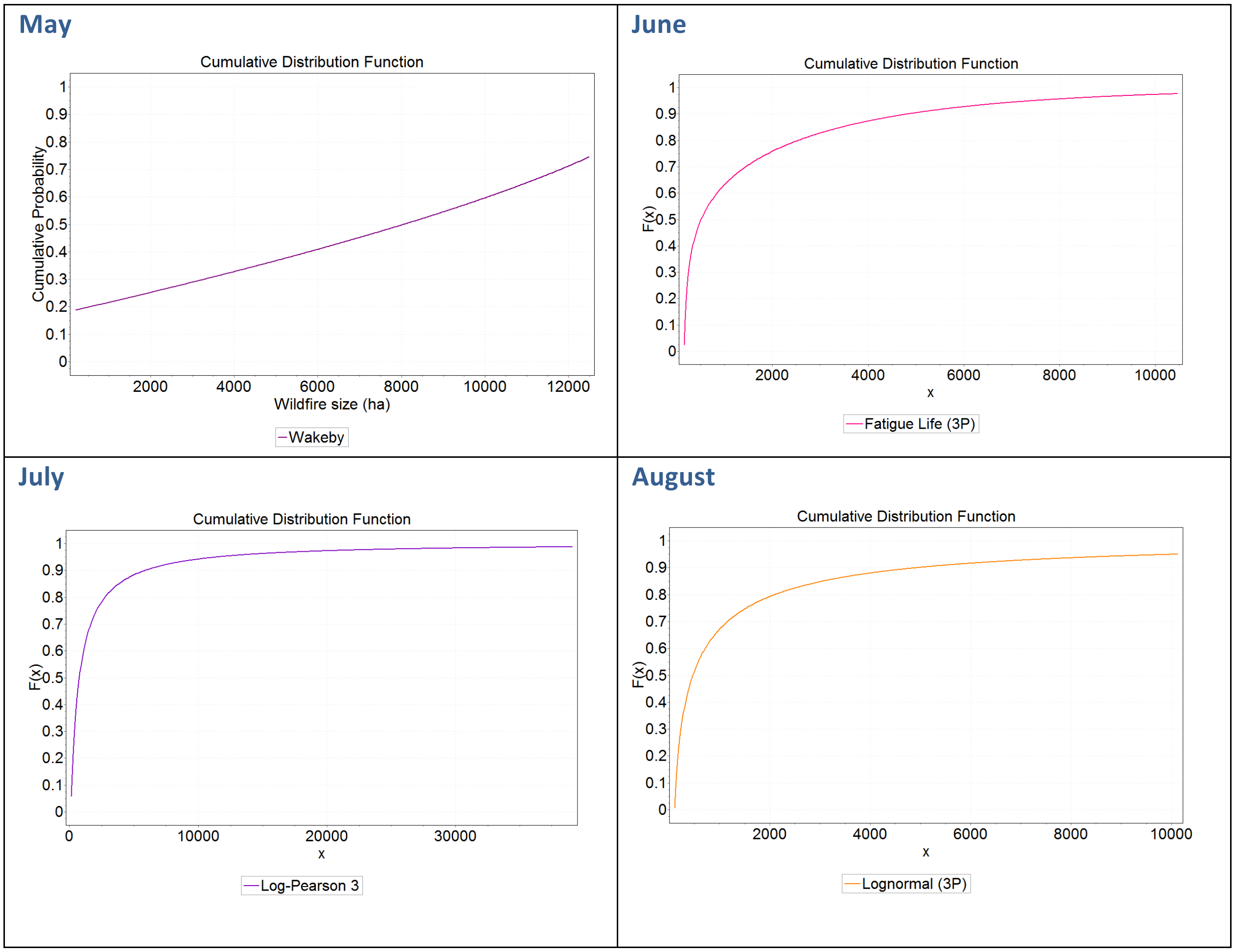


Figure 3.9 Cum. Distr. Function of wildfire sizes >= 100 ha with lightning cause.
Source: Canadian Forest Service, 2013

3.3.4 Weather Stream

Weather streams are among the mandatory inputs for the PrometheusCOM engine (see also section 2.4.3 and Appendix B (Prometheus File Formats and GIS Compatibility). The inputs include information about actual or forecast temperature, relative humidity, precipitation, wind speed, wind direction, and FWI System values stored at a 1-hour resolution, for one or more days. Daily or hourly weather data can be entered manually, or imported as delimited text files. Prometheus uses a diurnal weather modelling function to generate hourly values from daily weather inputs.

Environment Canada collects and publishes information on climatic conditions of particular locations throughout the country (Environment Canada, 2016). At the completion of each decade, Environment Canada updates its climate normals and averages for as many locations and as many climatic characteristics as possible. The climate normals, averages and extremes offered on Environment Canada's website are based on Canadian climate stations with at least 15 years of data between 1981 and 2010 (Environment Canada, 2016). For the purpose of this research conducted in the Nechako Lakes Electoral District, the closest weather station from which weather related data are available, is located at Smithers Airport (see Figure 3.10). This weather station is located at Latitude 54°49'29.000" N and Longitude: 127°10'58.000" W and its elevation is 521.8 metres above sea level. Although the exact topography and climate in and around Smithers will differ from each location in the Southside, it should be noted that specific variability of climate is generally low. The climate data available from this weather station are therefore adopted as being sufficiently representative for our research purposes.

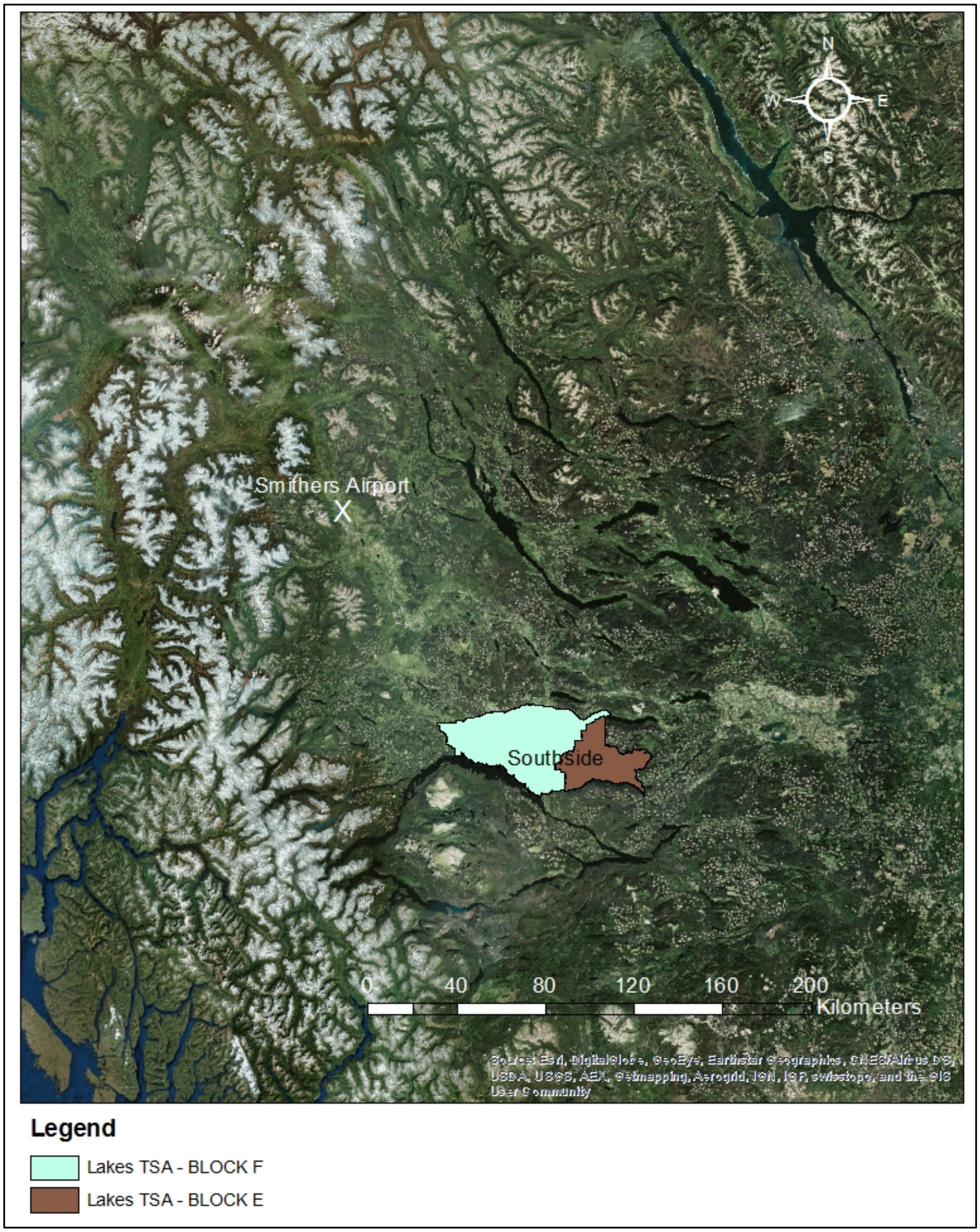


Figure 3.10 Location of Smithers Airport.

Sources: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, cNES/Airbus DS, USDA, USGS, AEX, Getmapping, AeroGrid, IGN, IGP, swisstop and the GIS User Community

Climate Normals from 1981-2010 for Smithers Airport are given in Table 3.13 and are used for this study. The average relative humidity was used as specified. Wind Data for Smithers Airport are presented in Table 3.14. Although the distribution of wind direction is known, the weather stream input data must be fixed to a certain value for each simulation. It was therefore decided to adopt the most frequent wind direction as the fixed value for all iterations of the baseline strategy. The sensitivity analyses were used to clarify the impact of wind direction on results.

The weather stream used in the simulations, is given in Table 3.15 (Environment Canada, 2016). The daily weather streams were derived from these data. It is important to note that on a monthly basis, a constant daily weather stream will be applied in the simulations. Any variation will therefore not be correlated with weather variation on a daily basis. Instead, sensitivity analysis will be performed on the weather stream variables as listed in Tables 3.13, 3.14 and 3.15. In this way, each of the simulations will be tested to verify that these variables do not affect the acceptance or rejection of hypotheses posed.

Table 3.13 Climate Normals from 1981-2010 at Smithers Airport, BC

	Month					
Variable	Apr	May	Jun	Jul	Aug	Sep
Temperature						
Daily Maximum (°C)	10.9	15.9	19.4	21.6	21.3	15.8
Daily Minimum (°C)	-1.3	2.9	6.5	8.6	7.9	4
Precipitation						
Precipitation (mm)	23.8	38.1	55.2	45.6	43.8	53.8
Wind						
Average Speed (km/h)	7.1	6.6	6	5.2	4.7	4.5
Most Frequent Direction	SE	N	N	N	N	SE
Maximum Hourly Speed (km/h)	61	51	57	50	46	56
Humidity						
Average Relative Humidity - 0600LST (%)	82	82.5	84	87.9	91	92.6
Average Relative Humidity - 1500LST (%)	43.6	42.8	48.3	50.8	50.4	57.1
Average Relative Humidity - (0600LST+1500LST / 2)	62.8	62.65	66.15	69.35	70.7	74.85

Source: www.climate.weather.gc.ca/climate_normals

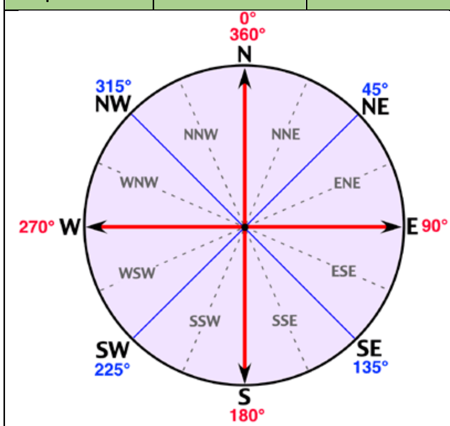
Table 3.14 Probability density of wind direction from Apr-Sept for Smithers Airport, BC.

Month	Wind Direction																Sum
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	
Apr	0.02	0.04	0.02	0.04	0.02	0.06	0.20	0.20	0.10	0.06	0.02	0.04	0.04	0.04	0.04	0.04	1.0
May	0.06	0.04	0.02	0.02	0.04	0.06	0.15	0.14	0.08	0.04	0.02	0.02	0.06	0.06	0.12	0.10	1.0
Jun	0.10	0.06	0.02	0.02	0.02	0.04	0.08	0.14	0.08	0.02	0.04	0.04	0.04	0.06	0.10	0.15	1.0
Jul	0.06	0.04	0.04	0.02	0.06	0.06	0.16	0.12	0.06	0.04	0.04	0.04	0.04	0.06	0.10	0.08	1.0
Aug	0.03	0.04	0.03	0.03	0.03	0.04	0.14	0.15	0.10	0.03	0.01	0.04	0.04	0.08	0.09	0.10	1.0
Sep	0.02	0.01	0.02	0.03	0.02	0.08	0.16	0.20	0.11	0.04	0.03	0.02	0.04	0.07	0.08	0.07	1.0

Statistics based on observations taken between 08/2013 - 01/2015 daily from 7am to 7pm local time.
Source: www.windfinder.com/windstatistics/smithers_airport?fspot=smithers_bc

Table 3.15. Monthly weather stream data applied to the wildfire simulations.

Month	Minimum temperature	Maximum temperature	Relative humidity	Precipitation (mm)	Minimum wind speed (km/h)	Maximum wind speed (km/h)	Wind direction (degrees from N)	Wind Direction
April	-1.3	10.9	62.8	0.79	0.83	61	135	SE
May	2.9	15.9	62.65	1.23	0.85	51	0	N
June	6.5	19.4	66.15	1.84	0.63	57	0	N
July	8.6	21.6	69.35	1.47	0.54	50	0	N
August	7.9	21.3	70.7	1.46	0.48	46	0	N
September	4	15.8	74.85	0.79	0.36	56	135	SE



Sources:

www.windfinder.com/windstatistics/smithers_airport?fspot=smithers_bc
www.physicalgeography.net
www.climate.weather.gc.ca/climate_normals

3.3.5 Elevation, slope and aspect

Digital elevation data were obtained from NRC databases (Natural Resources Canada, 2015b) and are optional inputs in the PrometheusCOM engine as described in section 2.4.3. Figure 3.11 displays the elevations in the Southside, which range from 710 to 1438 metres above sea level. Slope and Aspect were derived from elevation using ArcGIS. Figure 3.12 displays the slopes in the Southside. This information was derived using the 'Surface' function in ArcGIS Spatial Analyst. Slopes range from 0% to 41.6% with the vast majority of terrain being slightly undulated and a few areas with steep hills. Figure 3.13 displays the aspects in the Southside. This information was derived using the 'Surface' function in ArcGIS Spatial Analyst.

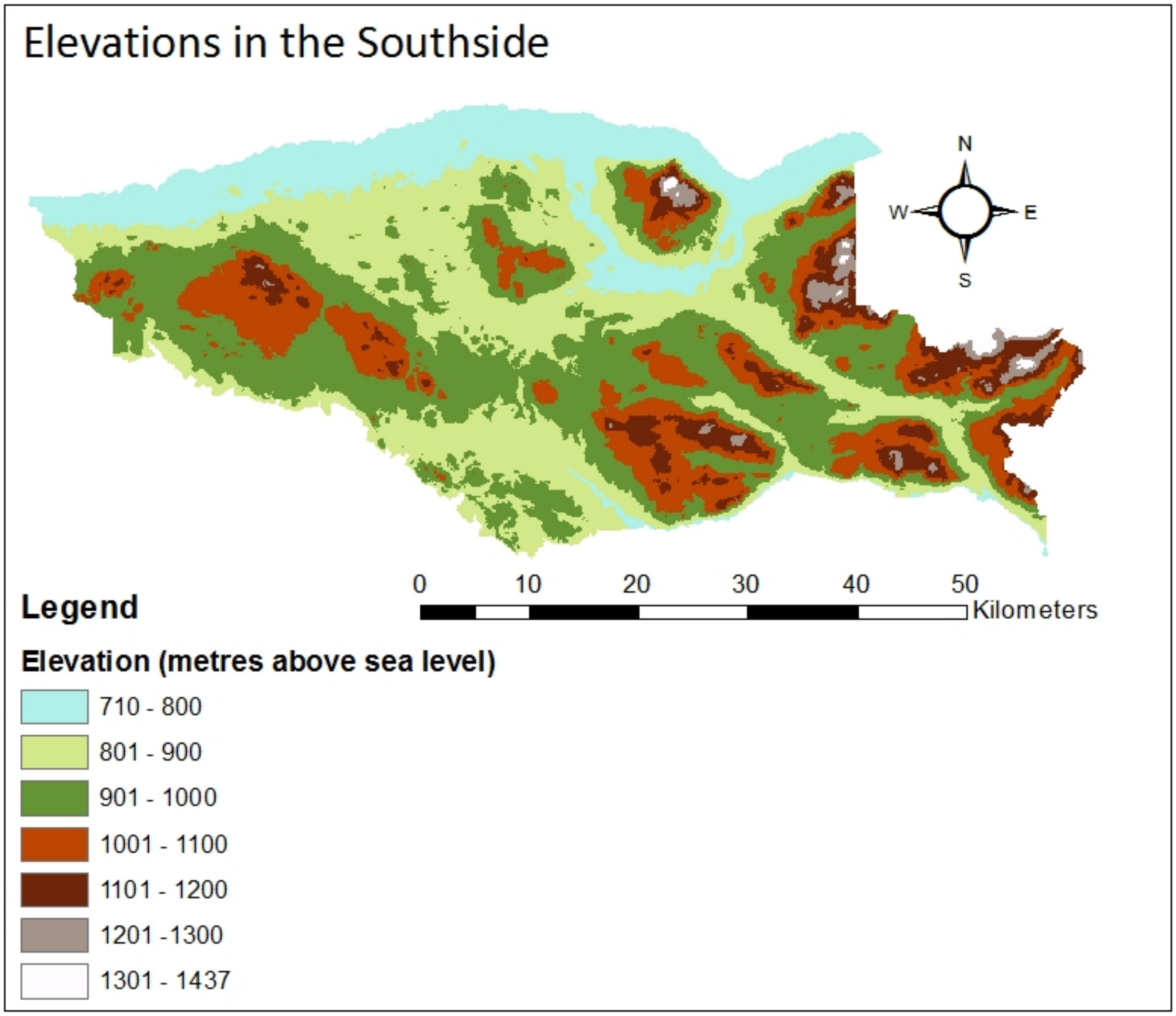


Figure 3.11 Elevations in the Southside.
Source: Natural Resources Canada, 2015b

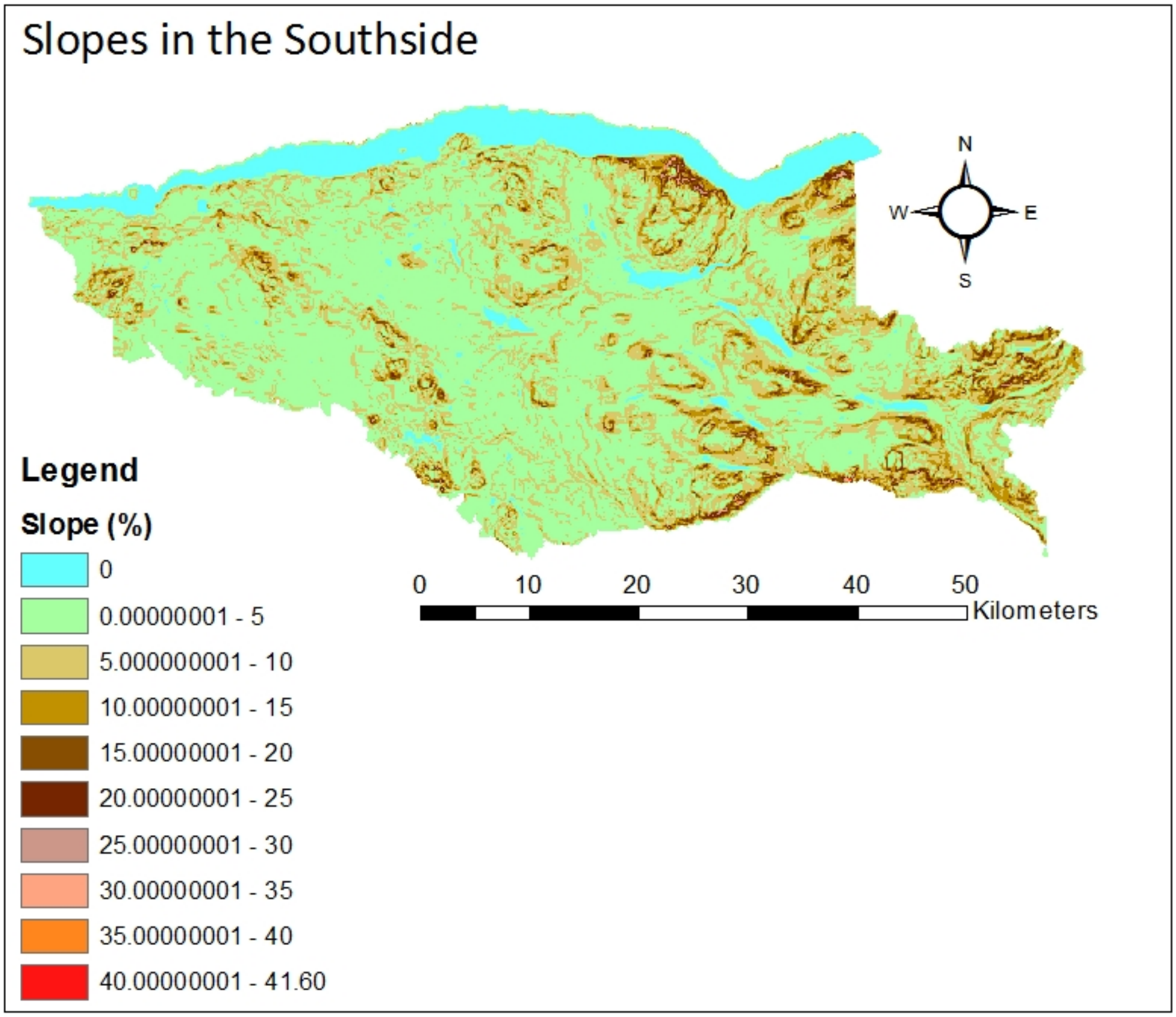


Figure 3.12 Slopes in the Southside.
Source: Natural Resources Canada, 2015b

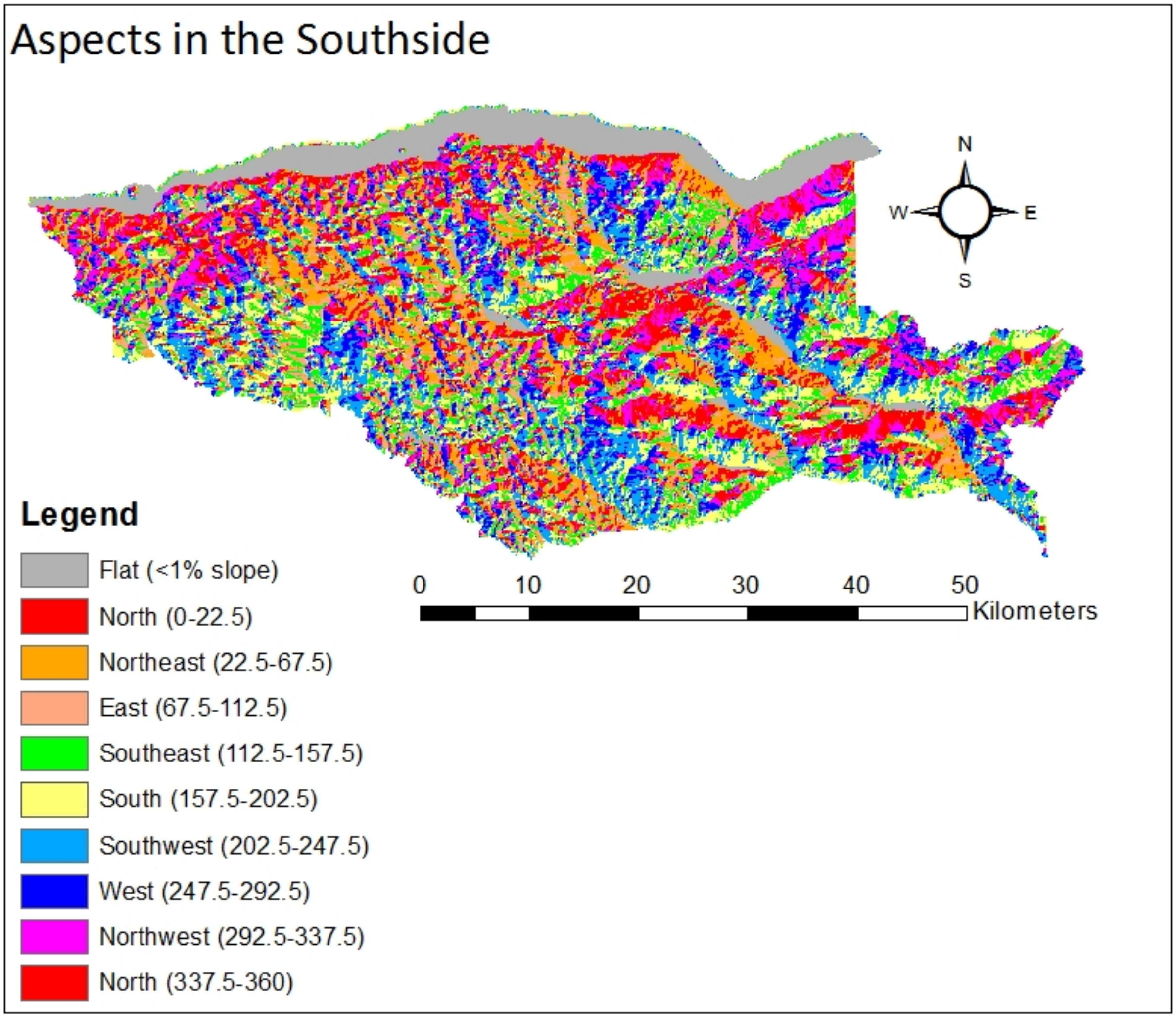


Figure 3.13 Aspects in the Southside.
Source: Natural Resources Canada, 2015b

3.3.6 Wildfire probability as a function of distance to road

The point data file in the National Fire Database database (NFDB_point_20131108.shp) contains information on ignition location for large fires in terms of latitude and longitude. However, the polygon file (NFDB_poly_20140210.shp) does not contain this information. Therefore, logic has to be derived for the ignition location of wildfires in this study. Two parameters that could play a role are distance to road (this section) and land use (section 3.3.7). Based on the outcome of this analysis, a baseline ignition map is constructed (section 3.4.4).

Figure 3.14 and Table 3.16 display the wildfires over 100 hectares by cause and distance to road from 1950-2012.

For wildfires caused by lightning, the relationship is as follows:

$y = -0.037\ln(x) + 0.1382$
with $R^2 = 0.2044$ and $n = 236844$
where y = hectares burned and x is the distance (km) to a road.

For wildfires caused by human activity, the relationship is as following:

$y = 0.0554\ln(x) + 0.0856$
with $R^2 = 0.04$ and $n = 236844$
where y = hectares burned and x is the distance (km) to a road.

From these data it can be concluded that for wildfires over 100 hectares, which are in the scope for this study, no significant relationship exists between the average number of hectares burned per hectare and the distance to a main road. See Figure 3.15 and Figure 3.16. While it is acknowledged that this relationship may exist for smaller fires (Liu et al, 2013), for the purpose of this study and the 100 ha plus wildfire sizes, the assumption is made that there is no such relationship. The implication of this assumption is that for model simulations, random ignitions can be made independent of distance to road. This will be covered in section 3.4.4.

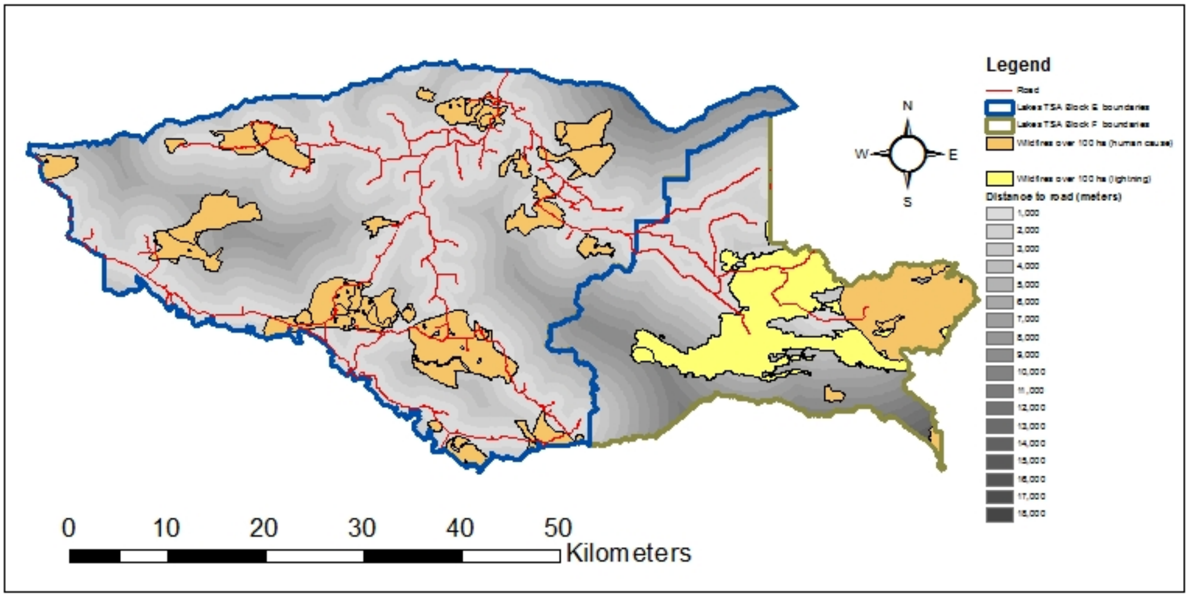


Figure 3.14 Wildfires in the Southside (1950-2012) by cause and distance to road

Table 3.16 Area burned by cause and distance to road, Southside, BC from 1950-2012

Distance to road (km)	Area (ha)	Burned area (ha)		Area burned per ha *)	
		Lightning	Human	Lightning	Human
0-1	71828	4516	12268	0.06	0.17
1-2	46466	4164	7488	0.09	0.16
2-3	32072	2604	4305	0.08	0.13
3-4	22131	2856	2497	0.13	0.11
4-5	17893	1915	2156	0.11	0.12
5-6	15636	1512	2142	0.10	0.14
6-7	12365	1283	1732	0.10	0.14
7-8	8514	1446	1257	0.17	0.15
8-9	5654	1182	769	0.21	0.14
9-10	2520	196	464	0.08	0.18
10-11	744	4	234	0.01	0.31
11-12	328	0	2	0.00	0.01
12-13	248	0	0	0.00	0.00
13-14	175	0	54	0.00	0.31
14-15	141	0	123	0.00	0.87
15-16	70	0	43	0.00	0.61
16-17	30	0	0	0.00	0.00
17-18	18	0	0	0.00	0.00
Total	**236844**	**21678**	**35534**		

*) Area burned (ha) in the 63-year period from 1950-2012, per hectare of surface

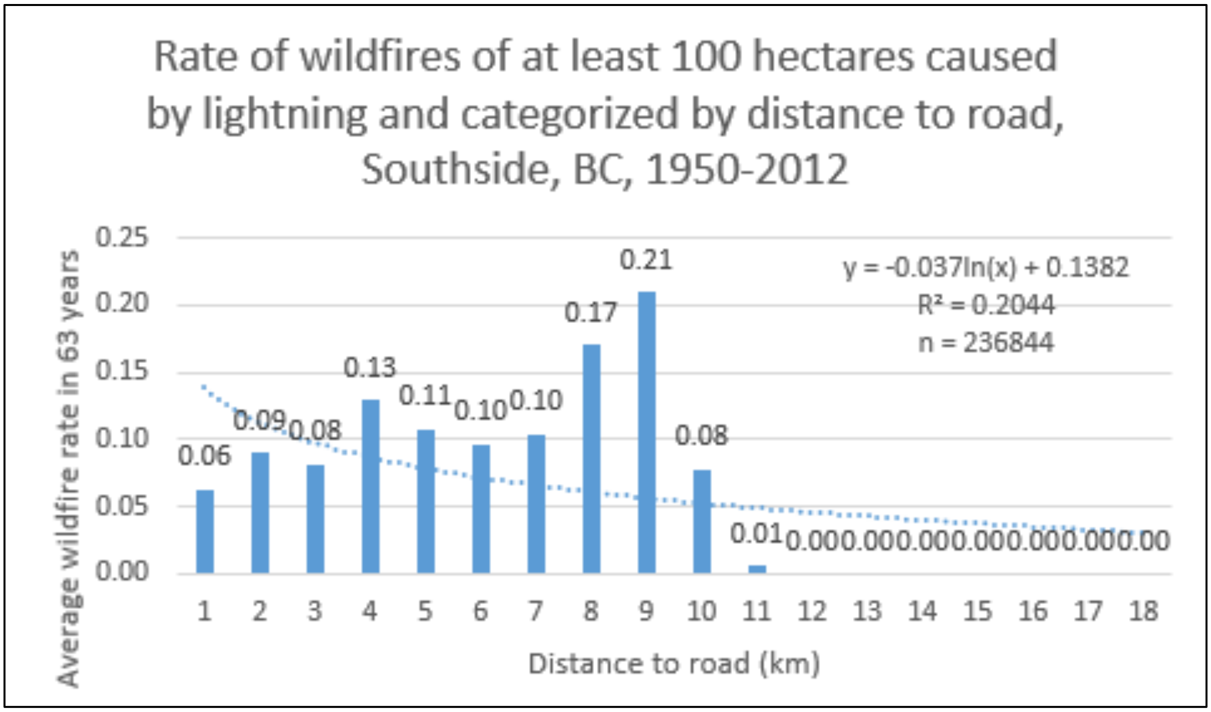


Figure 3.15 Area burned by wildfires >= 100 ha with lightning cause by distance to road.

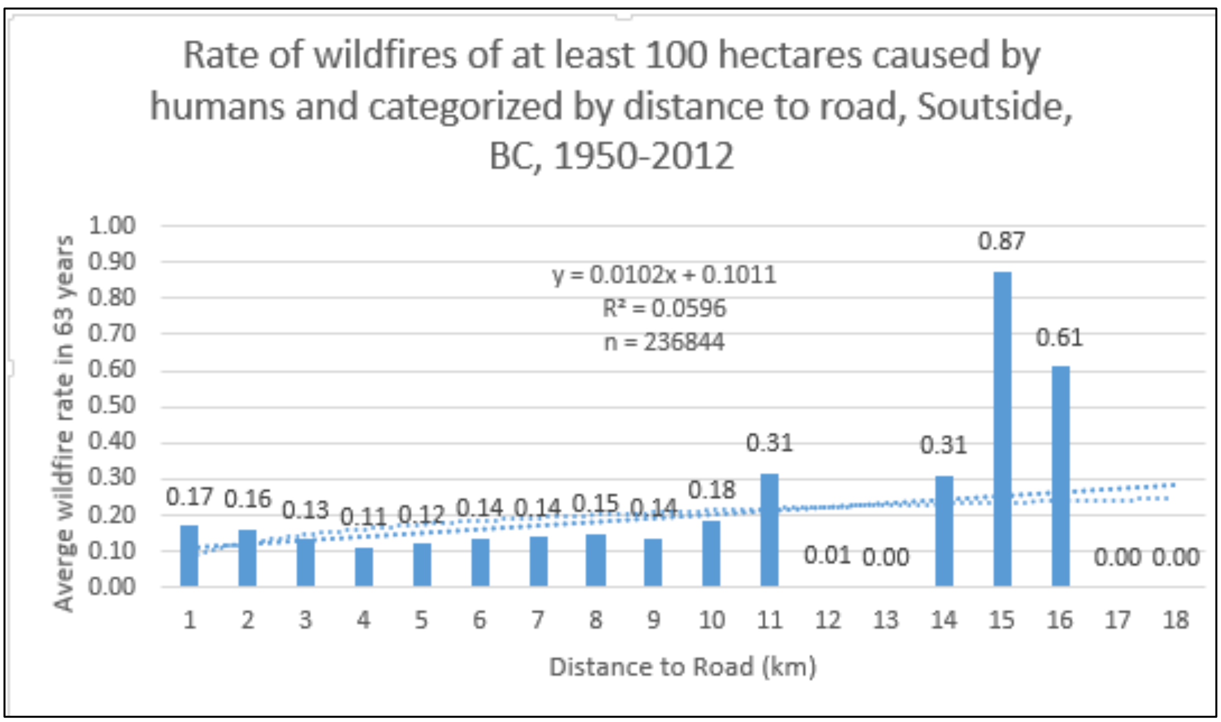


Figure 3.16 Area burned by wildfires >= 100 ha with human cause by distance to road.

3.3.7 Historic wildfire probability per land use

Wildfire history in the Southside was used as a basis for determining the baseline ignition map. In order to determine whether the ignition logic should include information on land use for each cause (human or lightning), the total area of historical wildfires per cause and land use was analyzed. Table 3.17 displays the total area burned in proportion to the total area, by cause and land use in the Southside between 1950 and 2012. Only 9 out of 18 land use categories experienced wildfires between 1950 and 2012: young forest, old forest, recently logged, wetlands, agriculture, barren surfaces, urban, range lands and residential agricultural mixes. Based on these findings, only these 9 land uses were included as potential ignition locations. The observed ratios of burned versus total area for these 9 land use categories varies from 0 to 0.31 as shown in the columns in Table 3.17. The observed relative area burned for wildfire with human cause is higher for barren surfaces (0.31), wetlands (0.21) and young forest (0.21) than it is for old forest (0.07). As well, the observed probability of wildfire caused by lightning is higher for barren surfaces (0.20) than it is for wetlands (0.13) and old forest (0.13). Both sets of observations appear to be counterintuitive, as barren land could be expected to result in lower relative areas burned.

These observations based on historic data reveal an apparent limitation, as any changes in land use throughout the period from 1950-2012 were not linked with changes in wildfire events. Categorization of land as 'barren surface' in the most recent release of the national database may well be the direct result of the occurrence of past wildfires. Land uses such as 'selectively logged', 'recently burned' 'young forest' and 'old forest' represent snapshots in time. Land ownership could have changed at least once within this 63-year period as well. The value of using land use in combination with wildfire cause when using these historic data for impact assessment is thus limited as structural or temporary shifts in land use or land ownership may very well either have been caused by, or have been the cause of the occurrence of wildfires themselves. In reality, a consistent correlation between land use, cause and wildfire probability would be expected if land use were constant. However, the data analyzed do not show a consistent trend for all land uses during the 63-year period.

Based on these observed data it was decided that ignition location should be considered as equally probable across the above-mentioned 9 land use categories. When generating event lists using the baseline ignition map, random points will therefore be generated in ArcGIS. It should be noted that the spread of wildfires is still directly influenced by fuel type and thus land use. In other words, although the ignition probability was assumed to be random as part of the model simulations, wildfire size would still be influenced by land use and cause.

Section 3.4.4 elaborates on the baseline ignition map and the event list generation is explained in section 3.4.8. It is noted that the total area in Table 3.17 comprises 236875 hectares whereas the total area in Table 3.16 is 236844. This difference is the result of the difference in clipping criteria, where the Shapefiles of 'land use' and 'distance to road shapefiles' are compared with wildfire occurrence on a pixel-by-pixel basis. The outer edges of the polygons in the scope area are the root cause of this discrepancy.

Table 3.17 Area burned by cause and land use, Southside, BC, 1950-2012

Land Use Category	Total area (ha)	Human Cause		Lightning cause	
		Burned area (ha)	Ratio of burned/total area	Burned area (ha)	Ratio of burned/total area
Calculation	**A**	**B**	**B/A**	**C**	**C/A**
Young forest	123352	26178	0.21	13603	0.11
Old forest	37451	2679	0.07	5006	0.13
Recently logged	27215	2350	0.09	1065	0.04
Fresh water	28152	0	0	0	0
Alpine	0	0	0	0	0
Wetlands	6444	1381	0.21	845	0.13
Agriculture	11018	2196	0.20	175	0.02
Sub-alpine avalanche chutes	0	0	0	0	0
Glaciers and snow	0	0	0	0	0
Selectively logged	415	0	0	0	0
Shrubs	0	0	0	0	0
Recently burned	0	0	0	0	0
Barren surfaces	1043	327	0.31	210	0.20
Urban	315	71	0.23	0	0
Range Lands	1108	183	0.17	0	0
Mining	45	0	0	0	0
Recreation activities	65	0	0	0	0
Residential agricultural mixtures	221	38	0.17	0	0
Total	**236875**	**35534**		**20904**	

3.4 Model Calibration and Preparation

This section presents the controllable and uncontrollable elements of the firebreak simulation model scenarios for Southside. It also discusses the model input and output indicators for the evaluative aspect of the firebreak strategies under consideration as well as the technical components of the simulation trials.

3.4.1 Establish Controllable variables

Table 3.18 summarizes the base case (no firebreaks) and firebreak strategies to be tested. It specifies the land ownership codes from Table 2.6, to which firebreaks are applied.

Five firebreak strategies are compared to a baseline strategy with wildfire simulations based on an unchanged land use grid. They are tested by implementing 100 metre firebreaks around defined areas with values at risk, and are implemented by placing these breaks around: (1) private property (PRIV); (2) old growth forest within Timber Supply Areas (TSA1); (3) provincial parks (PARK); (4) community forests (COMF); and (5) awarded woodlots (WLOT). Firebreaks are placed around land use type 'Old Forest' as described in Table 2.5, as part of the TSA1, PARK, COMF and WLOT strategies. The remaining 890 hectares or 0.57% of the Southside cover crown and federal lands and were considered too small for consideration to be included in the scope of this thesis for any of the fuel treatments. The area required to implement these firebreaks differs per scenario, as specified in Table 3.18.

As a result of choosing grid cell size of 10,000 square metres in our ArcGIS maps, the firebreak width will also have to minimally be 100 metres. Fuel management projects have worked with different fuelbreak widths ranging from 30 up to 200 metres (Dallyn et al, 2002). The conversion of land use grids to create firebreaks is explained in section 3.4.7 below.

Table 3.18 Base Case and Firebreak Strategies

Name of Strategy	Area to be protected	Land Ownership category	Land ownership code	Surface in Southside		Firebreak area	
				Ha	%	Ha	% of Southside
BASE	None (Baseline)	All	All	236844	100	0.0	0.0%
PRIV	Private property	Around privately owned land	40	33784	14.26	12748	5.4%
TSA1	Old Forest in TSA	Crown grants - prov adm. – Forest Management unit (TSA)	62	155354	65.59	24949	10.5%
PARK	Old Forest in Prov Park	Crown - prov. Admin – Prov. Park Class A	63	7854	3.32	1578	0.67%
COMF	Old Forest in Community Forest	Community Forest	79	25168	10.63	3041	1.28%
WLOT	Awarded Woodlot	Crown – Awarded Woodlot licence (Schedule 'B' land. Private portion, Schedule 'A', is coded 40-N).	77	13332	5.63	5257	2.22%

3.4.2 Establish uncontrollable variables and scenarios

Table 3.19 presents the results of categorized settings and assigned specification values for weather related parameters of the simulation model. These assignments are based on average occurrences for the settings over the recent history for Southside data.

Table 3.19 Specification of weather-related parameters

Variable	Setting	Specification
Temperature	**Cold**	3 degrees Celsius below the minimum or maximum temperature.
Temperature	**Warm**	3 degrees Celsius above the average minimum or maximum absolute temperature.
Humidity and Precipitation	**Wet**	20% above average humidity and 20% above the average daily precipitation.
Humidity and Precipitation	**Dry**	20% below the average humidity and 20% below average daily precipitation.
Wind Speed	**Windy**	20% above the maximum or minimum wind speed.
	Windstill	20% below the maximum or minimum wind speed.
Wind Direction	**North**	Wind only occurs at an angle of 0 ^{0}.
	East	Wind only occurs at an angle of 90 ^{0}.
	South	Wind only occurs at an angle of 180 ^{0}.
	West	Wind only occurs at an angle of 270 ^{0}.

Table 3.20 lists the weather related parameters applied per scenario and also used in sensitivity analysis. Simulations were performed *ceteris paribus* for each of the baseline and the five firebreak treatments (Table 3.18).

Wildfire event settings were derived from the trends previously presented in Table 3.3, Wildfire Counts. This table clearly shows an upward trend in wildfire count in the Nechako Lakes Electoral District throughout the 63-year period analyzed. In the 30-year period 1950-1979 there were 20 wildfires, in the 30-year period 1980-2009 there were 28 wildfires and in the 3-year period from 2010-2012 there were 32 wildfires. This suggests the possibility of climate change having an upward effect on the wildfire rate. In Table 3.20 therefore, the wildfire event rate is set to double in unfavourable weather and is only half the average in favourable weather. Favourable and unfavourable values for monthly 'climate Normals' (temperature, relative humidity, wind speed, and wind direction) are presented in Table 3.20 below as modified values for historical Southside 'climate Normals' given previously in Table 3.13 as adjusted according to Table 3.19 above.

Table 3.20 Monthly Uncontrollable weather parameters by scenario. *)

Scenario	Month	Parameter setting							
		Temp.		Relative humidity	Precipi-tation	Wind speed		Wind direction	Wildfire count
		Min	Max			Min	Max		λ (event rate)
		°C	°C	%	mm	km/h	km/h	°	100+ ha fires/month
Unfavourable	April	1.7	13.9	52.33	0.66	0.99	73.20	135	0.0051
	May	5.9	18.9	52.21	1.02	1.02	61.20	0	0.03056
	June	9.5	22.4	55.13	1.53	0.76	68.40	0	0.02038
	July	11.6	24.6	57.79	1.23	0.65	60.00	0	0.054
	August	10.9	24.3	58.92	1.22	0.58	55.20	0	0.0377
	September	7	18.8	62.38	0.66	0.43	67.20	135	0.0163
Average	April	-1.3	10.9	62.80	0.79	0.83	61	135	0.00255
	May	2.9	15.9	62.65	1.23	0.85	51	0	0.01528
	June	6.5	19.4	66.15	1.84	0.63	57	0	0.01019
	July	8.6	21.6	69.35	1.47	0.54	50	0	0.027
	August	7.9	21.3	70.70	1.46	0.48	46	0	0.01885
	September	4	15.8	74.85	0.79	0.36	56	135	0.00815
Favourable	April	-4.3	7.9	75.36	0.95	0.69	50.83	135	0.001275
	May	-0.1	12.9	75.18	1.47	0.71	42.50	0	0.00764
	June	3.5	16.4	79.38	2.21	0.53	47.50	0	0.005095
	July	5.6	18.6	83.22	1.76	0.45	41.67	0	0.0135
	August	4.9	18.3	84.84	1.75	0.40	38.33	0	0.009425
	September	1	12.8	89.82	0.95	0.30	46.67	135	0.004075

*) Wildfire counts based on Table 3.3 monthly historical averages. 'Unfavourable' monthly scenarios result in wildfire counts that are double monthly historical averages; 'Favourable' monthly scenarios result in wildfire counts that are one-half monthly historical averages.

3.4.3 Output indicators

3.4.3.1 Primary output indicators

Table 3.21 gives an overview of the primary Southside firebreak simulation model output indicators applied in this study. BASE represents the baseline in which no firebreaks are implemented. Results of each of the five firebreak strategies (PRIV, TSA1, PARK, COMF, and WLOT) are compared to the BASE scenario. Each of the five strategies has the goal to protect specific assets in the landscape through the application of 100 metre wide firebreaks around designated areas by removing any combustible vegetation. In the PRIV scenario, all areas with private property are protected. In the TSA1 scenario, firebreaks are implemented around all timber supply areas as well as around old forest growth within these areas. This same approach is taken in the PARK, COMF and WLOT strategies, representing respectively Provincial Parks, Community Forest and Awarded Woodlots.

Table 3.21 Primary firebreaks simulation model output indicators per firebreak strategy

Indicator Number	Primary Model Output Indicator	Indicator Description	Units
1	Area Relative to Firebreak	This indicator presents the total Southside area in 3 parts: (a) Total Southside Area (without firebreaks); (b) area inside of the designated firebreaks; and (c) area outside of the designated firebreaks	Hectares (ha)
2	Area Burned without firebreaks	Average annual area burned from all simulation trials for the Base Case (BASE - NO firebreaks in place)	Hectares (ha)
3	Area Burned with firebreaks	Average annual area burned from all simulation trials for each of the five firebreaks strategies in place (PRIV, TSA1, PARK, COMF, WLOT)	Hectares (ha)
4	Area Burned Change	Simple difference between area burned without firebreaks (BASE), and the area burned under each of the five firebreaks strategies in place (PRIV, TSA1, PARK, COMF, WLOT) (item 2 minus item 3)	Hectares (ha)
5	Area Burned Percentage Difference	Calculated percentage difference of change (item 4) relative to the total burned area without firebreaks, i.e., [(2-3)*100/2]	%

3.4.3.2 Secondary output indicators

This section describes secondary output indicators measured for each firebreak strategy.

At the height of the pine beetle infestation in British Columbia, the Canadian Forest Service at Natural Resources Canada conducted an impact analysis investigating the economic implications of various policy options for suppressing the mountain pine beetle infestation in two Forest Districts in central British Columbia (Patriquin et al, 2015). The effects of temporary increases in the Annual Allowable Cuts (AACs) in combination with subsequent reduction of timber supplies were measured across six main sectors of the economy, namely agriculture, forestry, domestic services, the public sector, visitors, and the rest of the economy. Economic variables included Gross Revenue, Net Regional Product, Royalties and Indirect taxes, gross wages and the number of employment positions.

Table 3.22 provides a summary of macro-economic indicators and major sectors used for impact assessment of each of the five strategies (PRIV, TSA1, PARK, COMF, WLOT). These macro-economic indicators and sectors were applied by Patriquin et al (2005) and have been adopted for this study (Table 3.18).

Table 3.22 Summary of Economic Indicators and Major Sectors used for Impact Assessment

Economic Indicators

Indicator	Explanation
Revenue	The gross amount of economic activity (in dollars) that takes place in the region on an annual basis. Revenue is the product of quantity and price in an economic market (for example, revenue is the total value of sales).
Net regional product (NRP)	The combination of all dollar payments for labour, capital, resource rents, and indirect taxes (for example, net regional product is the amount of "value-added" activity). Unlike revenue, net regional product represents the value of goods and services produced in the region in a year.
Royalties & indirect taxes	The dollar rents paid by firms to the government for use of publicly owned natural resources. Indirect taxes are any taxes other than income or corporate.
Labour income	The dollar amount paid by firms to employees (for example, salaries, wages, etc.)
Employment	The number of individuals who associate their job in an individual industry as their primary source of employment.

Major Sectors

Sector	Explanation
Agriculture	All agriculture (e.g. farming) and agriculture-related services (e.g. veterinary services)
Forestry	Logging, milling, and forestry-related services
Services	Domestic service expenditures on non-industry specific services by residents and local businesses. Industry-specific services are included under the specific sector being served. For example, forestry services are included in the forestry section.
Visitor*	Economic activity related to people visiting the region for the purpose of tourism, business, conventions, etc. The visitor sector is a distinct separation of visitor from domestic expenditures on accommodations, retail, transportation, and services.
Public	Education, social services, health, and government services.
Rest of the Economy (ROE) **	All remaining sectors of the economy, including retail, mining, construction, transportation, warehousing, etc.

* The many recreational opportunities attract a significant number of visitors each year, including regional visitors, visitors from the rest of the province, and long-haul visitors from North America, Europe, and Asia. Although accurate and timely information on the size and value of tourism in the study area is not available, Tourism BC (1998) produced a report entitled, *B.C. Visitor Study: Report on Travel In British Columbia--Northwest Region*, that summarizes travel patterns between 1995 and 1996. The northwest region, within which the study region lies, includes all areas north of the Highway 16 corridor between the Alberta border and the Queen Charlotte Islands. As the figures reported reflect a much larger geographic area than our study area, the information must be interpreted with some caution. Regardless of this issue, the report was an exhaustive attempt to measure the volume and value of travel in the province, and is the best source available.

** Mining is aggregated with the retail sector due to confidentiality constraints.

Source: Patriquin et al, 2005

Table 3.23 shows the data used in deriving the harvestable land base equivalent of 1% AAC in the Nadina Forest District. Patriquin et al (2005) report an area of 1,273,950 hectares of harvestable timber, representing 48.53% of a combined total area of 2,624,901 hectares in the Nadina Forest District. Scenario 1 in their study is used as the basis for our calculations. This scenario uses a 1,462,000 m^3 (42.24%) increase of AAC in the Nadina Forest District from 3,461,117 m^3 to 4,923,117 m^3. A 1% increase in AAC would therefore represent an additional area of 14,637 hectares with the same harvest level. The results of our simulations will be primarily measured as reduction in hectares of wildfire in the Southside. In order to get an estimated impact for the Nadina Forest District of each of the firebreak strategies, this reduction is multiplied by the surface ratio of 12.63 between the Nadina Forest District and the Southside.

The percentage reduction in burned area is applied to the Nadina District to obtain the impact in terms of secondary output indicators. Table 3.23 shows the surface relations between the Nadina Forest District, the Nechako Lakes Electoral District and the Southside. The historic average of annually burned area in the Nechako Lakes District is 318,271 hectares over 63 years, as reported in Table 3.5 and Table 3.7. The estimated area burned annually in the Nadina Forest District is therefore 2,047.12 hectares.

Table 3.23 Calculation of harvestable land base equivalent of 1% AAC in Nadina Forest District

Parameter	initial AAC	projected AAC	AAC increase	
Unit of measure	m^3	m^3	m^3	%
Amount	3461117	4923117	1462000	42.24
Parameter	AAC land base (ha)	Area available for timber harvesting		Area equivalent of 1% AAC increase
Unit of measure	ha	%	ha	ha
Amount	2624901	48.53%	1273950	14637
Parameter	Nadina	Southside	Southside to Nadina	Multiplier Nadina to Southside
Unit of measure	m^3	km^2	%	-
Amount	29903	2368.44	7.92%	12.62561011
Parameter	Historic average area burned (ha) in 63 years in Nechako	Estimated historic average area burned (ha) in 63 years in Nadina	Surface Ratio of Nadina to Nechako	Historic average annual area burned (ha)
Unit of measure	ha	ha	-	ha
Amount	318271	5051.92	0.405215508	2047.12

Derived from Patriquin et al, 2005

Table 3.24 lists the macro-economic impact per sector (in 2005 dollar values) resulting from a 1% increase in AAC in the Nadina Forest District, based on reported results by Patriquin et al (2005). The impact is calculated based on a 1,462,000 m^3 increase of AAC in the Nadina Forest District from 3,461,117 m^3 to 4923,117 m^3. The upper section in Table 3.24 displays the impact on the 42.24% (see Table 3.24) while the lower section shows the amounts on a basis of a 1% increase in AAC representing 14,637 hectares of harvestable timber in the Nadina Forest District.

Table 3.24 Macro-economic impact resulting from 1% AAC increase in Nadina Forest District

Sector	Macro-Economic Impact ($) from AAC increase				
	Gross Revenue	Net Regional Product	Royalties and indirect taxes	Gross wages	Employment positions
	($M)	($M)	($M)	($M)	
ALL	254	151	50	77	1211
Agriculture	0.55	0.2	0.1	0.1	14
Forestry	183.3	130.4	48	61.7	712
Service	2.5	2	0.4	1.5	88
Public	4	2.5	0.5	1.6	31
Visitor	3.8	1	0.1	0.8	36
Rest of the Economy	59.9	14.5	0.9	10.8	330
Sector	**Macro-Economic Impact ($) per % AAC increase**				
	Gross Revenue	Net Regional Product	Royalties and indirect taxes	Gross wages	Employment positions
	$	$	$	$	
ALL	6014342	3565282	1183693	1811050	0.287
Agriculture	13021	47	24	24	0.003
Forestry	4339417	30871	11363	14607	0.169
Service	59185	473	95	355	0.021
Public	94695	592	118	379	0.007
Visitor	89961	237	24	189	0.009
Rest of the Economy	1418064	3433	213	2557	0.078

Derived from Patriquin et al, 2005.

Table 3.25 specifies the key performance indicators per firebreak strategy for the simulation model. Annual firefighting cost savings are calculated by using the average cost of firefighting over the period from 2004 through 2015 as specified in Table 1.1. The total reduction in area burned is multiplied by $1125.20 (see also Table 1.1) to obtain the total annual firefighting cost savings. The macro-economic impact is calculated by combining the information in Tables 3.24 and 3.25. For each 14,637 hectares in reduction of area burned (Table 3.24) the dollar values as specified in Table 3.25 are applied to obtain the macro-economic impact per sector for each of the firebreak strategies.

The Secondary Output indicators are provided for each firebreak strategy (BASE, PRIV, TSA1, PARK, COMF, WLOT), by weather-related scenario (unfavourable, average, favourable – Table 3.20).

Table 3.25 Secondary output indicators and key performance indicators

Strategy ↓	Scenario ↓	key performance indicators (annual impact per hectare of fire break)							Rank
		Reduction in area burned	Additional Gross Revenue	Additional Net Regional Product	Additional Royalties and indirect taxes	Additional Gross wages	Additional Employment positions	Firefighting cost savings	
Unit of measure →		ha * km^{-1} * year^{-1}	CAN $	CAN $	CAN $	CAN $	persons	CAN $	
BASE	UNF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PRIV		72.19							
TSA1		84.52							
PARK		128.12							
COMF		189.32							
WLOT		116.86							
BASE	AVG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PRIV		17.59							
TSA1		22.68							
PARK		22.94							
COMF		52.52							
WLOT		29.71							
BASE	FAV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
PRIV		2.238							
TSA1		2.821							
PARK		3.358							
COMF		5.486							
WLOT		3.364							

Secondary Model Output Indicator	Key performance indicator description	Units
Reduction in Area Burned	This indicator presents the area burned compared to the Base Case ((BASE - NO firebreaks in place) (continuation from Table 3.20)	Hectares (ha)
Additional Gross Revenue	Added value from unburned timber claimed under the AAC	2015 CAN Dollars
Additional Net Regional Product	Added value from unburned timber claimed under the AAC	2015 CAN Dollars
Additional Royalties and Indirect Taxes	Added value from unburned timber claimed under the AAC	2015 CAN Dollars
Additional Gross Wages	Added value from unburned timber claimed under the AAC	2015 CAN Dollars
Additional Employment Positions	Added value from unburned timber claimed under the AAC	Number of Full-time Employees
Firefighting Costs Savings	Reduced costs value from unburned timber claimed under the AAC	2015 CAN Dollars
Rank	Rank for each indicator above assigned to each firebreak strategy by scenario	Integer rank

3.4.4 Baseline ignition map

The baseline ignition map presented in Figure 3.17 shows the areas with land uses that are considered to be variably susceptible to ignition in the baseline scenario (BASE, Average weather-related events). A buffer ring of 300 metres on the area exterior was clipped in order to exclude the area on the north side of Ootsa Lake and to reduce the chance of simulating wildfires that could spread outside the simulation area. In Figure 3.17 the identified ignition areas are assumed to be equally susceptible to wildfires. "No ignition" areas are assumed not to burn.

Based on the results presented in the previous sections, a baseline ignition map was derived covering only those land uses demonstrating any history of wildfires between 1950 and 2012. It is assumed that all ignition areas are equally susceptible to wildfires. These include the following land uses (Table 3.17):

- Young forest
- Old forest
- Recently logged
- Wetlands
- Agriculture
- Barren surfaces
- Urban
- Rangelands
- Residential agricultural mixes

The areas with mining (45 ha) and recreation activity (65 ha) were added to this map. These areas had no history of wildfire due to their small size, but this should not exclude them from future wildfire exposure. Fresh water was excluded from the baseline ignition map and selectively logged areas were not considered to be susceptible to ignitions based on history. In the Southside, no areas exist with the following land uses: alpine, sub-alpine avalanche chutes, glaciers and snow, shrubs and recently burned. There were large wildfires between 1900 and 1950 in the area, which seems to correspond with the relatively large proportion of Young forest (less than 140 years of age) in the Southside and no recently burned areas.

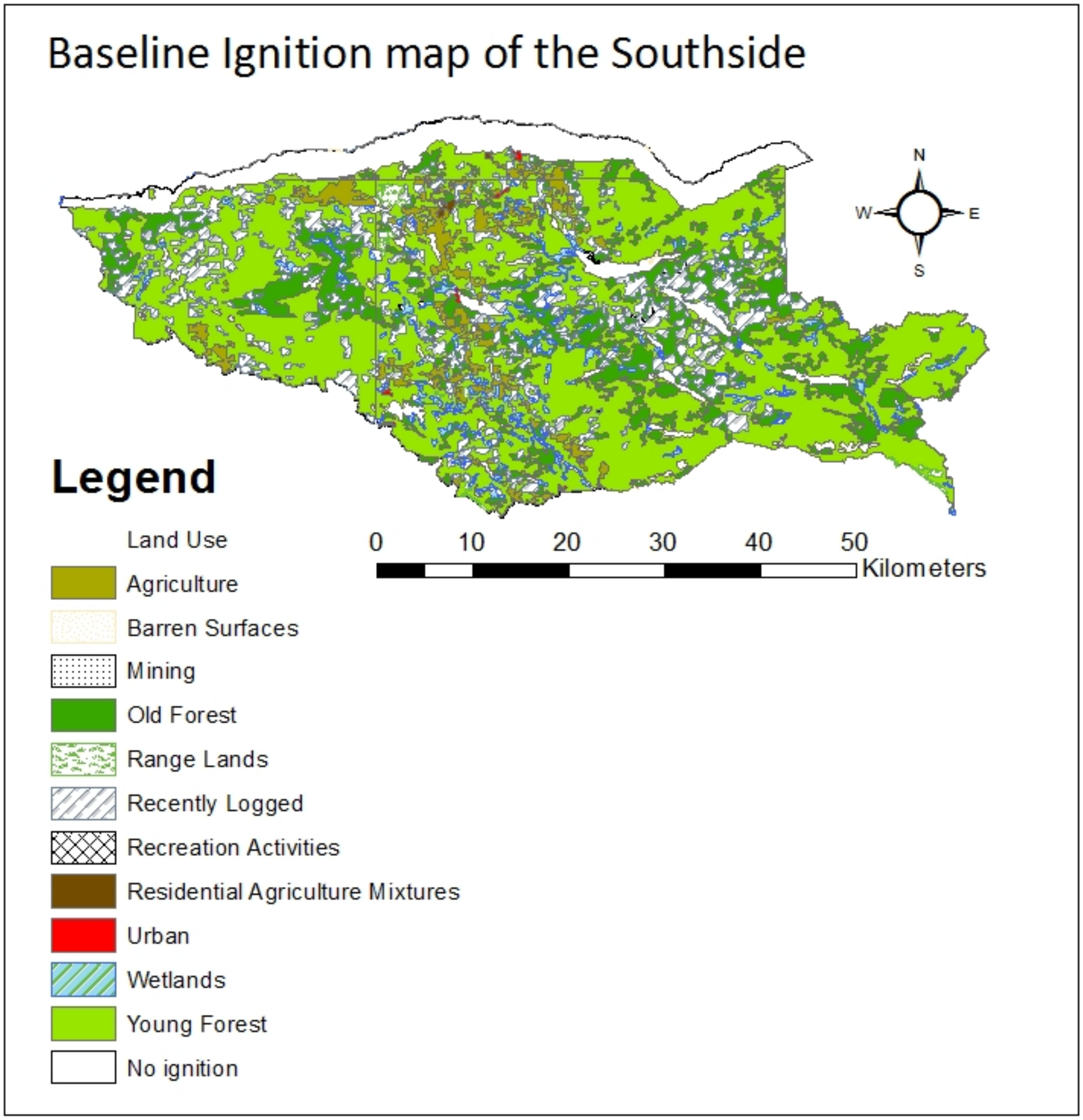


Figure 3.17 Baseline ignition map of the Southside.
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

3.4.5 Allocation of Fuel Type to Land Use type

The burn behaviour of vegetation on the entire simulation area of the Southside as determined by the existing fuel types will result in different areas being burned depending on the fuel treatment scenario. Land use types as described in Tables 2.8 and 2.9 and applicable to the Southside as listed in Table 3.26 have been allocated to the Fire Behaviour Prediction (FBP) System.

Table 3.26 Fuel Types defined in the Fire Behaviour Prediction (FBP) System

Fuel Type	Description
O1: Grass	Continuous grass cover, with no more than occasional trees or shrub clumps that do not appreciably affect fire behaviour. Two subtype designations are available for grasslands; one for the matted grass condition common after snowmelt or in the spring (O1-a) and the other for standing dead grass common in late summer to early fall (O1-b). The proportion of cured or dead material in grasslands has a pronounced effect on fire spread there and must be estimated with care.
M-2: Boreal Mixed wood Green	M2: Boreal Mixed wood Green: the second phase of seasonal variation in flammability (of M1), occurs during the summer. The rate of spread is weighted according to the proportion (expressed as a percentage) of softwood and hardwood components. In the summer, when the deciduous overstory and understory are in leaf, fire spread is greatly reduced, with maximum spread rates only one-fifth that of spring or fall fires under similar burning conditions.
D-1: Leafless Aspen	Pure, semi-mature trembling aspen stands before bud break in the spring or following leaf fall and curing of the lesser vegetation in the autumn. A conifer understory is noticeably absent, but a well-developed medium to tall shrub layer is typically present. Principal fire-carrying surface fuel are deciduous leaf litter and cured herbaceous material directly exposed to wind and solar radiation. In the spring the duff mantle (F and H horizons) seldom contributes to available combustion fuel because of its high moisture content.

Source: Natural Resources Canada, 2014; Parisien et al, 2005

The allocations of fuel types to land uses are presented in Table 3.27 below.

Table 3.27 Allocation of fuel type to land use type

Land Use	Fuel Type Allocation	
Description	**Descriptive name**	**Fuel Type**
Agriculture	Standing Grass	O-1b
Alpine	Vegetated non-fuel	Vegetated non-fuel
Barren Surfaces	Non-fuel	Non-fuel
Fresh Water	Water	Non-fuel
Glaciers and Snow	Non-fuel	Non-fuel
Mining	Non-fuel	Non-fuel
Old Forest	Boreal Mixed wood - Green (95% Conifer)	M-2 (95 PC)
Range Lands	Standing Grass	O-1b
Recently Burned	Vegetated non-fuel	Vegetated non-fuel
Recently Logged	Vegetated non-fuel	Vegetated non-fuel
Recreation Activities	Vegetated non-fuel	Vegetated non-fuel
Residential Agriculture Mixture	Vegetated non-fuel	Vegetated non-fuel
Selectively Logged	Vegetated non-fuel	Vegetated non-fuel
Shrubs	Standing Grass	O-1b
Sub Alpine Avalanche Chute	Non-fuel	Non-fuel
Urban	Matted Grass	O1-a
Wetlands	Vegetated non-fuel	Vegetated non-fuel
Young Forest	Boreal Mixed wood - Green	M-2

3.4.6 Calibration of wildfire duration versus size in Pandora

Pandora uses wildfire duration as one of its inputs (see also Appendix F- "Pandora Input File Requirements"). However, the model in this thesis uses wildfire size as input. For this reason, a mathematical equation was required to derive wildfire duration from wildfire size to justify the Pandora input requirement. Calibration of wildfire duration in the baseline scenario against wildfire size was derived using our selected data from the National Fire Database (Canadian Forest Service, 2013) to derive the linear form. The resulting regression equation is as follows:

$$Y = (X + 3041.3) / 260.01$$

where Y denotes the predicted wildfire duration (in hours) and x denotes wildfire size (in hectares). The line fits the historical data of n=240 wildfires with a correlation coefficient of 99.71% of variance explained. This equation is used to derive wildfire duration (x) from wildfire size (Y). Pandora only processes information on an hourly basis. Therefore, in the input file the value of Y will be rounded off to the closest integer.

In order to confirm to the Pandora requirements for integer data, the continuous regression durations were determined for alternative wildfire sizes. Generated wildfire sizes were translated to full hourly amounts by truncating the decimal remainder, as illustrated in Table 3.28 below.

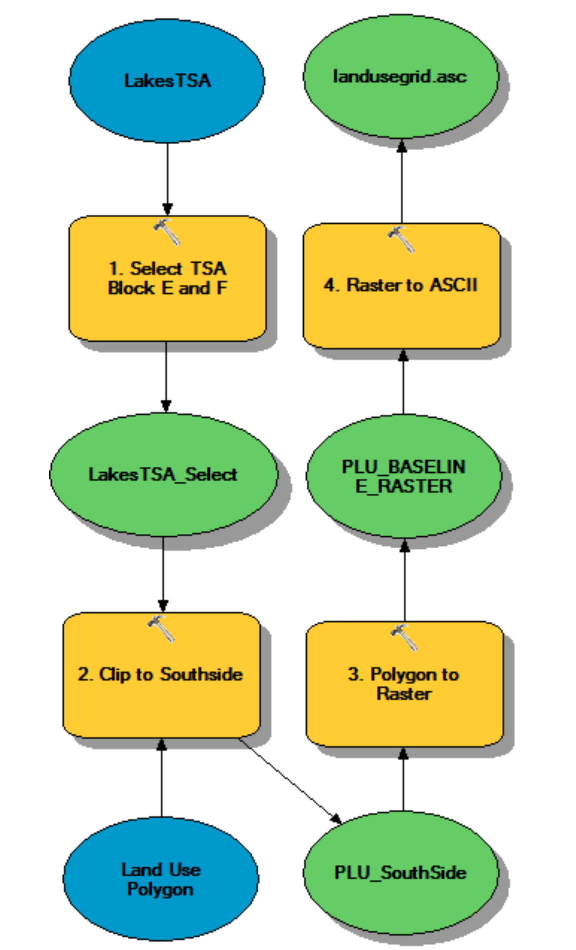
Table 3.28 Wildfire size versus duration

Wildfire size	Wildfire duration (h)	Integer input in Pandora (h)
100	12.08	12
500	13.62	13
1000	15.54	15
10000	50.16	50
40000	165.54	165

3.4.7 Converting land use grids with ArcGIS ModelBuilder

For each of the fuel treatment strategies, ArcGIS *ModelBuilder* was used to schedule ArcToolBox activities. This ArcGIS application was used as a visual modelling tool to create, edit, and manage the various data management workflows by stringing together sequences of geoprocessing tools and feeding the output of one tool into another tool as input.

Figure 3.18 displays the process flow applied in ModelBuilder to generate the baseline scenario (BASE – no firebreaks, Average weather-related variables). The *ArcToolbox* functions in ArcGIS that were applied included: Analysis Tools (Select, Clip, Spatial Join, Buffer) and Conversion Tools (Polygon to Raster, Raster to Point and Raster to ASCII). Using the Spatial Analyst Tools menu in ArcGIS, mapped algebraic expressions were utilized to convert fuel types to non-fuel for each of the applicable land ownership codes as part of a particular scenario. The details of this process are explained in Figure 3.18 below.

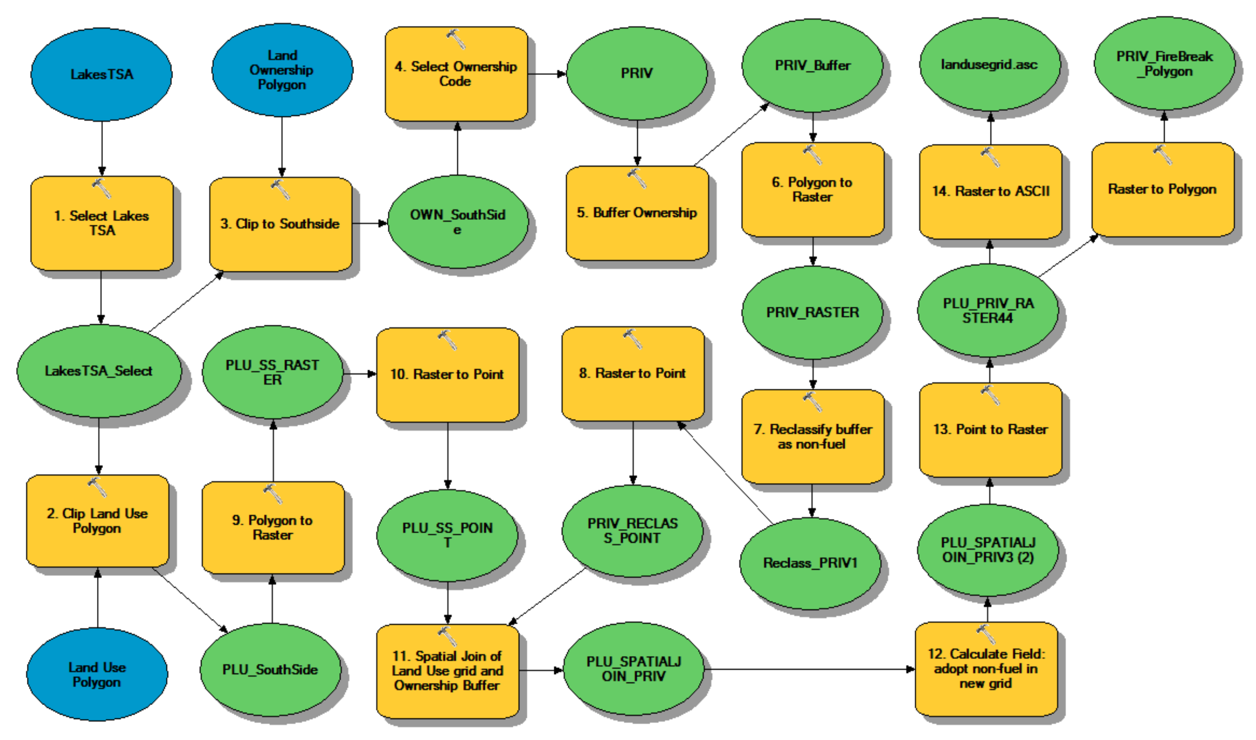


ModelBuilder steps:

1. **Select TSA Blocks E and F**
   The **Select** function in ModelBuilder (menu: Analysis Tools → extract) extracts features from an input feature class or input feature layer, typically using a select or Structured Query Language (SQL) expression and stores them in an output feature class.
2. **Clip area to be limited to Southside**
   The **Clip** function in ModelBuilder (menu: Analysis Tools → Clip) extracts input features that overlay the clip features. This tool is used to cut out a piece of one feature class using one or more of the features in another feature class as a cookie cutter. This is particularly useful for creating a new feature class—also referred to as study area or Area Of Interest (AOI)—that contains a geographic subset of the features in another, larger feature class.
3. **Convert Polygon to Raster**
   The Conversion function in ModelBuilder (menu: Conversion Tools → To Raster → Polygon to Raster) converts an ASCII file representing raster data to a raster dataset.
4. **Convert Raster to ASCII**
   The Conversion function in ModelBuilder (menu: Conversion Tools → From Raster → Raster to ASCII) converts a raster dataset to an ASCII text file representing raster data.

Figure 3.18 ModelBuilder process flow for Baseline Scenario.
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

Figure 3.19 displays the process flow applied in ModelBuilder to generate the firebreak strategy for the private woodlots strategy, PRIV (Table 3.18). The firebreaks for the other 4 strategies (TSA1, PARK, COMF and WLOT) are similar to this scenario, with the difference that the ownership field is selected with the appropriate value to create the non-fuel buffer zones for each scenario.



ModelBuilder Steps for the TSA1 firebreak strategy:

1. **Select** Lakes TSA to extract only the Lakes Timber Supply Area
2. **Clip** Land Use Polygon to the size of the Soutside area
3. **Clip** the Lakes TSA to the size of the Southside area
4. **Select** value 40 of the OWN field in the Land Ownership polygon, corresponding to Private Property
5. **Create a Land Ownership Buffer Polygon** around the Private Land Ownerhip polygon using a distance of 100 metres.
6. **Convert** the resulting Land Ownership Buffer Polygon to Raster.
7. **Reclassify** the Land Ownership Buffer Raster as non-fuel with a value of 44 representing non-fuel. The reclassify function in ModelBuilder (menu: Spatial Analyst Tools → Reclass) is used to reclassify or change the values in a Raster.
8. **Convert** the non-fuel Land Ownership Raster dataset to Point features.
9. **Convert** the Land Use Polygon to Raster.
10. **Convert** The Land Use Raster to Point features.
11. **Spatial Joint** of Land Use and Land Ownership Point features. The **Spatial Join** function in ArcGIS (menu: Joins and Relates → Join → Join data from another layer based on spatial location) joins attributes from one feature to another based on the spatial relationship. The target features and the joined attributes from the join features are written to the output feature class.
12. **Calculate Field**: adopt non-fuel in new Land Use grid.
13. **Convert** Land Use Point features to Raster
14. **Convert** Land Use Raster to ASCII
15. **Convert** Land Use Raster to Polygon

Figure 3.19 ModelBuilder process flow for PRIV Firebreak strategy.
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

Figure 3.20 displays the mapping result of the ModelBuilder model run for the PRIV scenario. All private property is entirely surrounded with a 100 metre wide buffer consisting of non-fuel, while all other land use values remain intact to retain their original fuel value. Figures 3.21 through 3.24 display the Modelbuilder results with firebreaks around old forests in respectively Timber Supply Areas (TSA1), Provincial Parks (PARK), Community Forests (COMF) and Woodlots (WLOT) firebreak strategies.

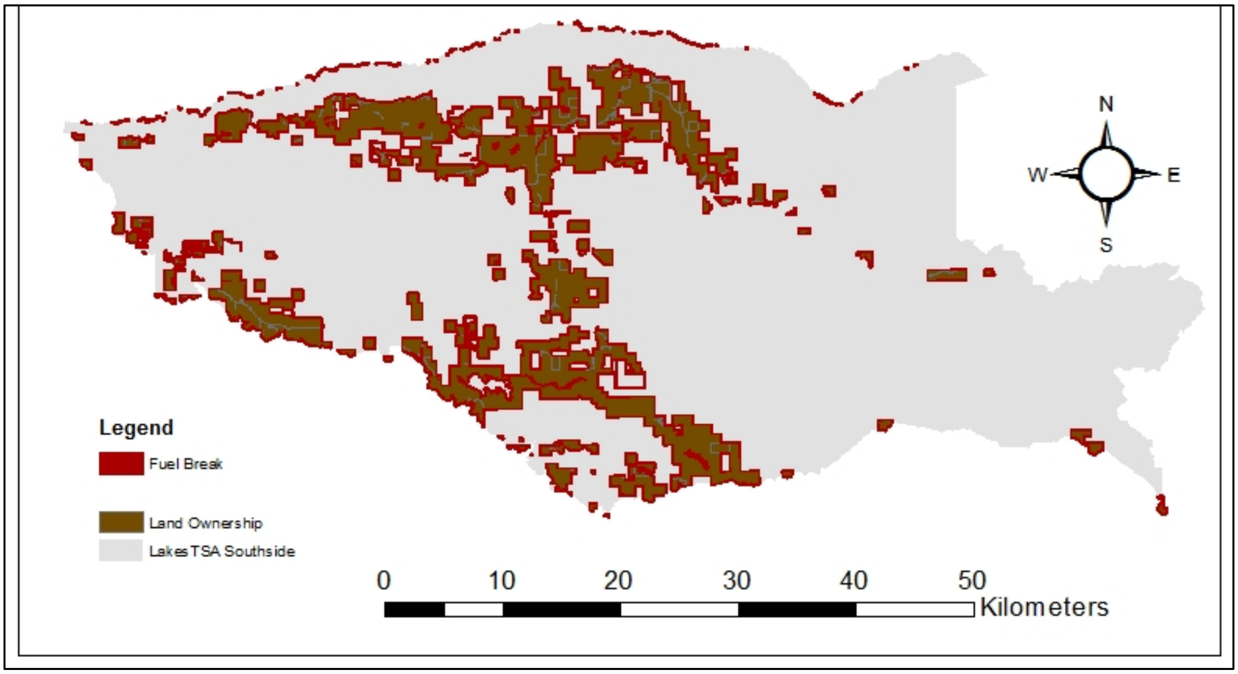


Figure 3.20 ModelBuilder mapping results for PRIV (Private Ownership)
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

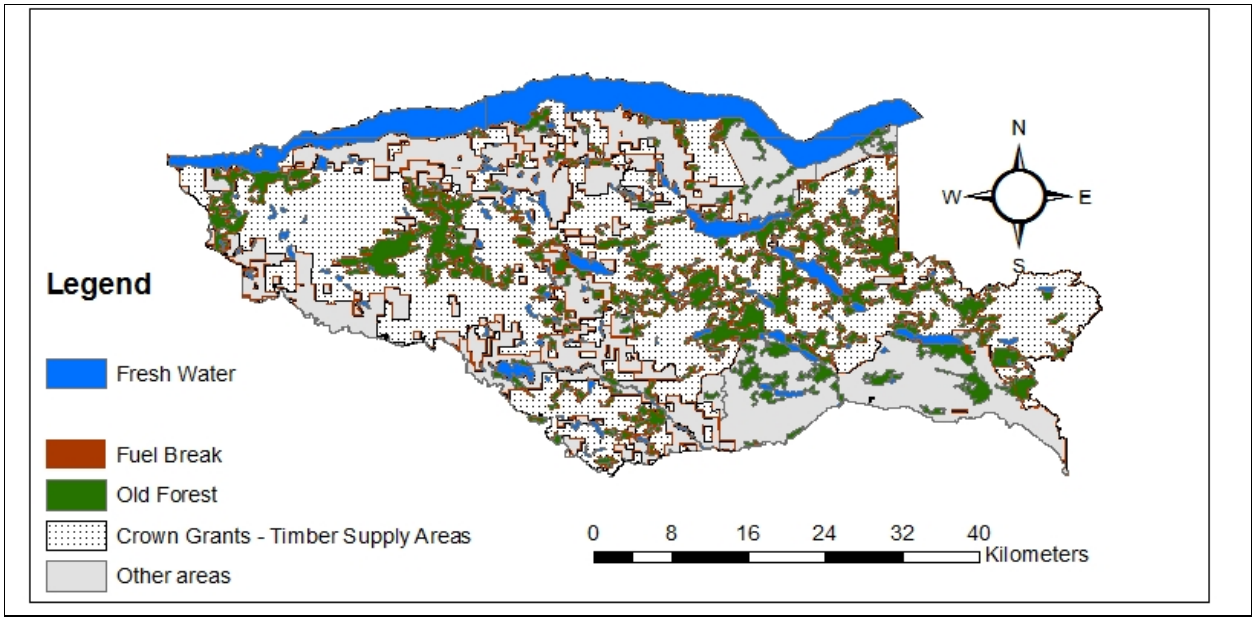


Figure 3.21 ModelBuilder mapping results for TSA (Timber Supply Area) Firebreaks (TSA1).
Source: http://cwfis.cfs.nrcan.gc.ca

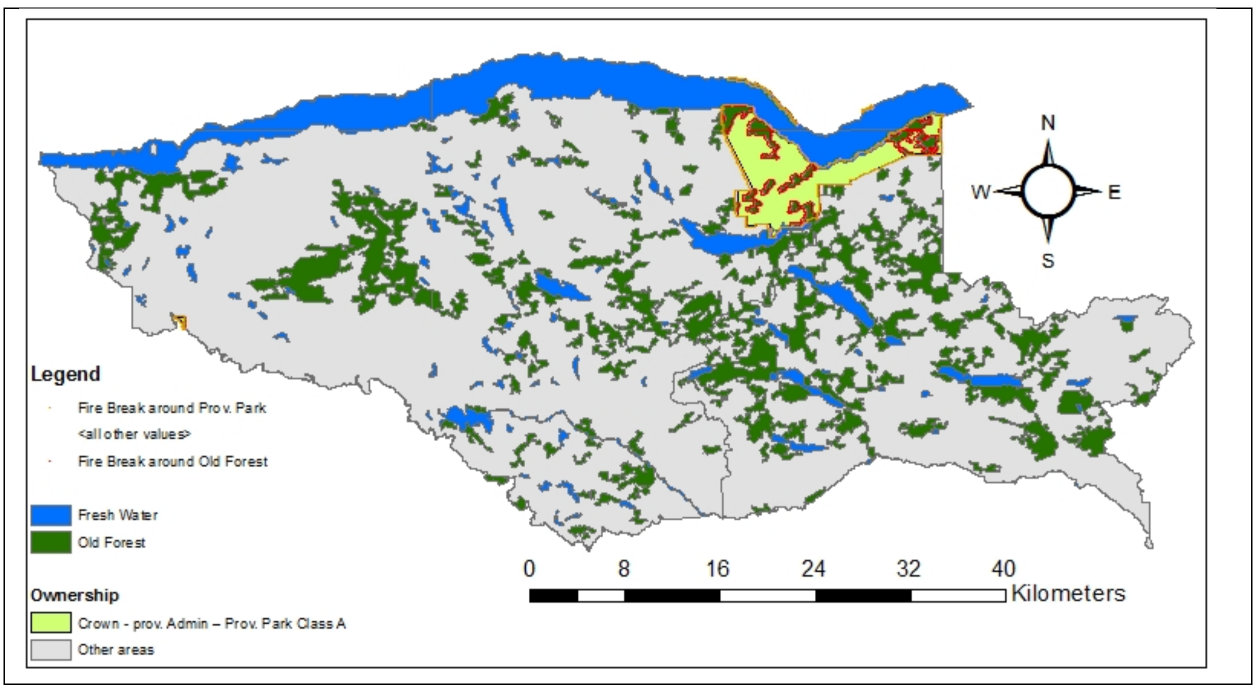


Figure 3.22 Modelbuilder maspping results for Provincial Park Firebreaks (PARK).
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

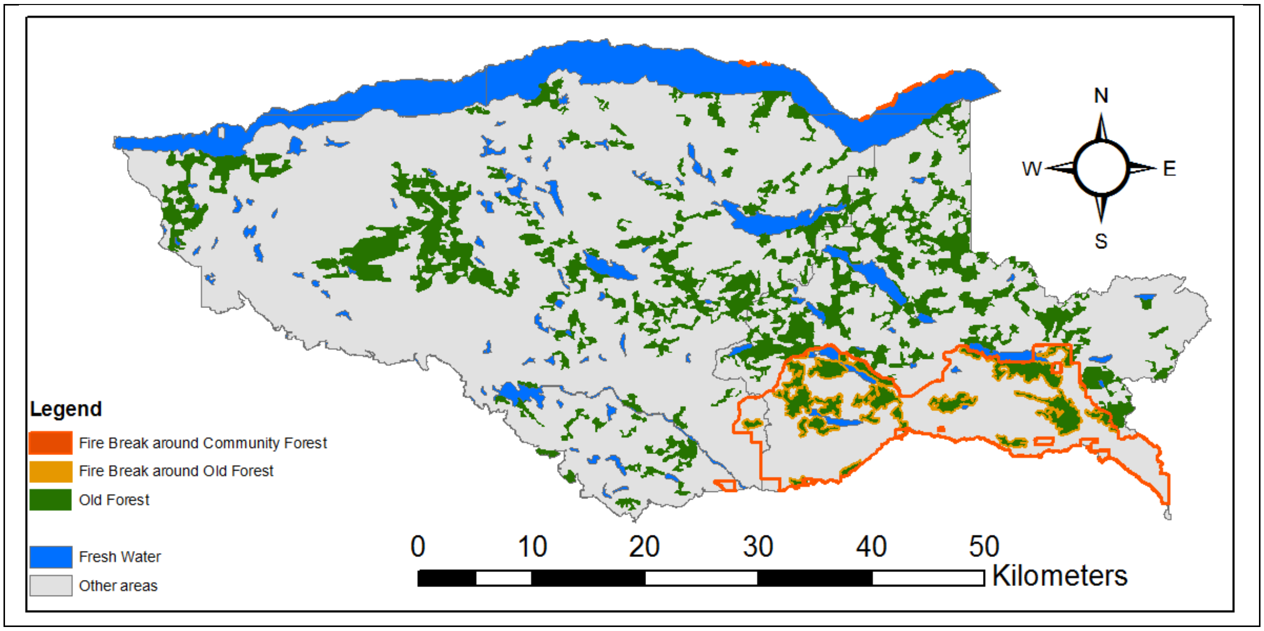


Figure 3.23 ModelBuilder mapping results for Community Forest Firebreaks (COMF)
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

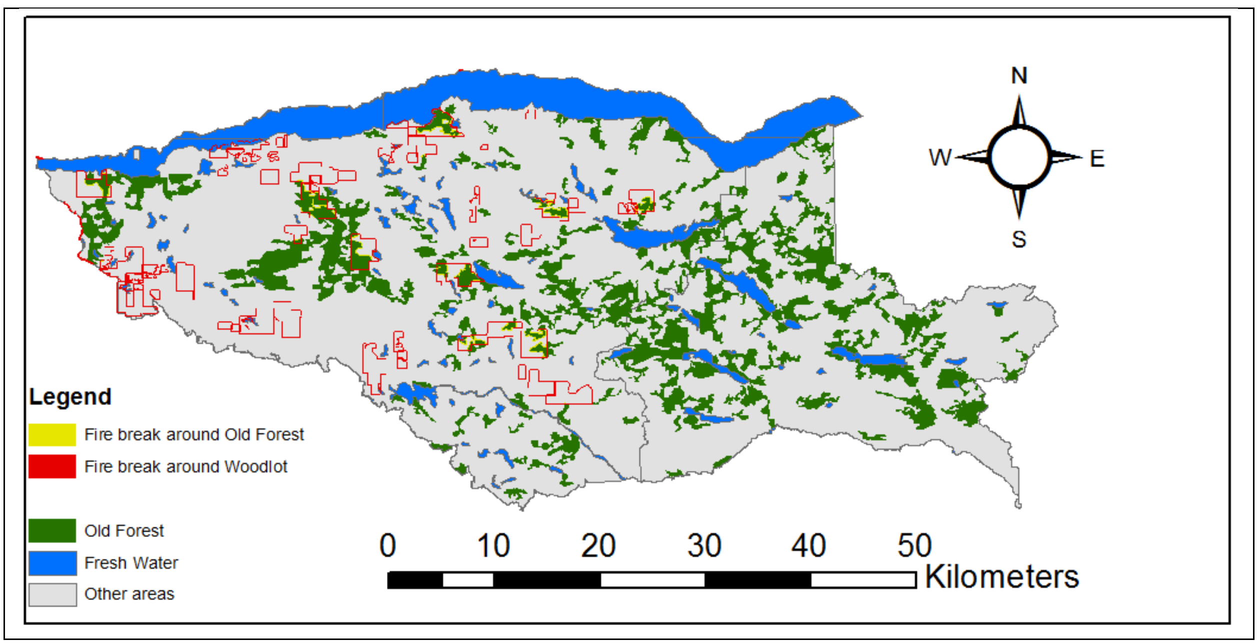


Figure 3.24 ModelBuilder mappng results for Woodlot Firebreaks (WLOT).
Sources: Canadian Forest Service, 2013, www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

3.4.8 Event List Generation

Figure 3.25 specifies the process steps involved in deriving the simulation model event list used as input for Pandora.

The variables symbols used are denoted as follows:

- **W** = simulation length (months)
- $\mathbf{F_M}$ = fire number in simulation month
- $\mathbf{C_M}$ = counter in simulation month
- **M** = month

The process steps are as follows:

1. Set simulation window (months) **W**. For a simulation period of 10,000 years, **W** will have value 1 at the beginning of the simulation and ends with value 120000 at the end of the simulation run. Set **M** = 1 (first month) and initialize $\mathbf{F_M}$ = 0 (numbers of fires).
2. Determine monthly wildfire count $\mathbf{C_M}$ based on a random sample from the corresponding probability function (section 3.3.1).
3. Determine the cause of the wildfire (human or lightning) based on a random sample from the corresponding probability density function (see section 3.3.2).
4. Determine wildfire size (ha) based on a random sample from the corresponding probability density function (see section 3.3.3).
5. Determine ignition location based on a random sample from the base ignition baseline map (see section 3.4.4).
6. Add 1 to the Fire number in this simulation month. $\mathbf{F_M}$ = $\mathbf{F_M}$ + 1
7. Add 1 to Month. **M** = **M** + 1.

The resulting event list is prepared using *Microsoft Excel* and transformed into a flat input file using *Microsoft Notepad* as explained further in section 3.4.10 below.

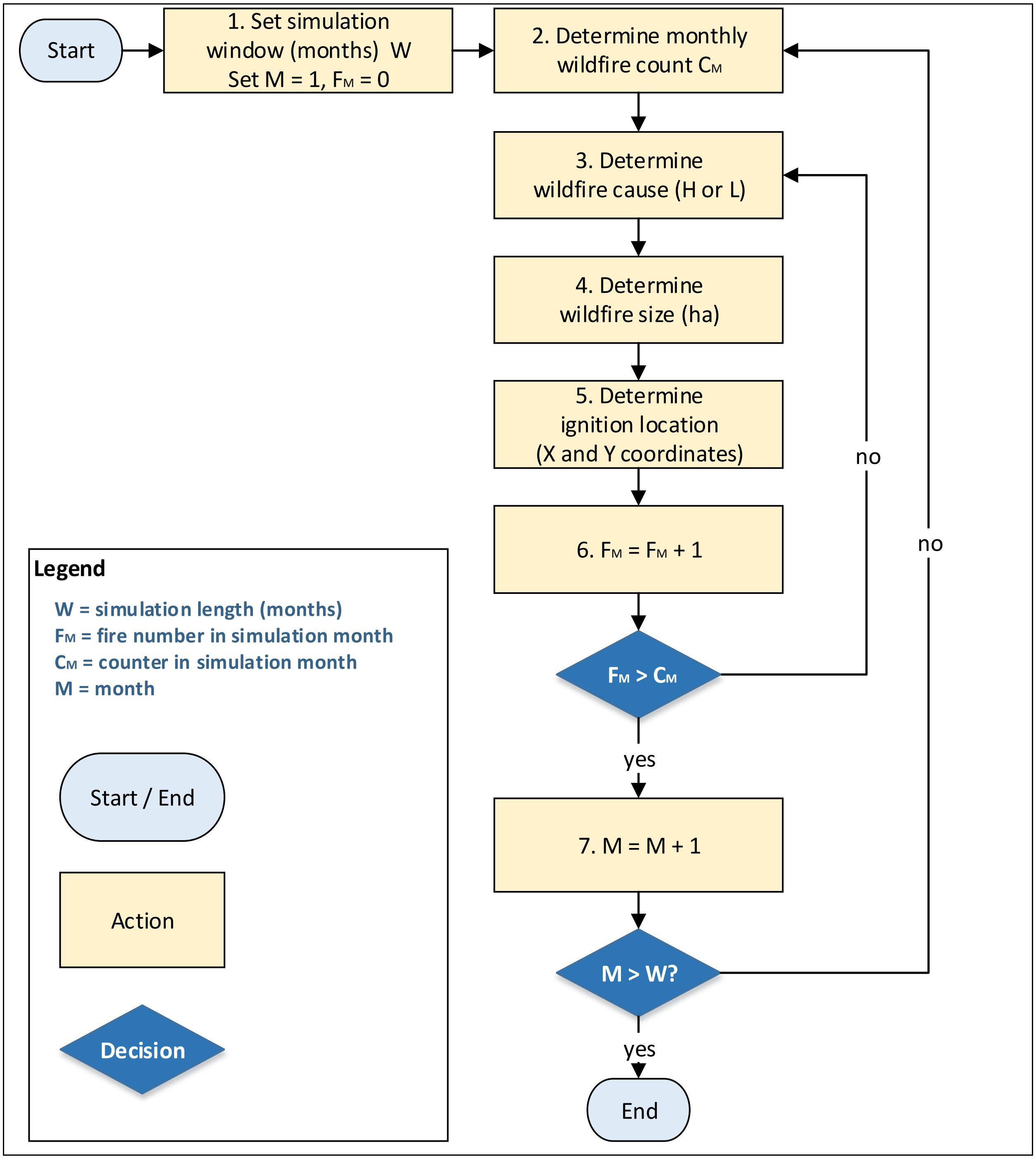


Figure 3.25 Script for event list generation

3.4.9 Simulation Trial Parameters

A simulation batch spanning a 10,000-year period was generated for each of the months between April and September for the Southside. Based on probability density functions derived, there are 1.64 wildfires of at least 100 hectares on average during each 20-year period. The simulation is performed on the assumption that simulations will not have to take into account a past wildfire. Or at least, the effect of past wildfires will be equally minimal for all simulations. Wildfires would normally cause a change in land use to 'recently burned'. Given that the probability of a wildfire occurring in the same area within a number of 20-year periods is low, the simulation is assumed to have no memory. In other words, a batch of 10,000 events can be simulated individually or at once, as if there was never a wildfire before. With an average of 1.64 large 100-hectare wildfires in 20 years, the probability that a large wildfire will occur in the same area is small. The wildfire would result in the area undergoing a land use change to 'recently burned' and it wouldn't yield a similar fire if it would burn for the second time. Removing the interdependence between present, past and future wildfire events will not diminish the validity of testing different firebreak strategies.

Table 3.29 shows an example of a 20-year event window in the Southside, which is the BASE case for file preparation as input for Pandora simulations. The interpretation of this BASE case example is as following:

- In June 2016 there is a wildfire caused by lightning with a size of 162 hectares
- In May 2030 there is a wildfire caused by human activity with a size of 391 hectares.
- No second or third events occur in any of the months within this particular simulated period

Table 3.29 Example of the Excel file event list generated for a 20-year window

SIMULATION	FIRST EVENT						SECOND EVENT					
YEAR	April	May	Jun	Jul	Aug	Sep	Ap	Ma	Ju	Jul	Au	Sep
2016			20160615L162									
2017												
2018												
2019												
2020												
2021												
2022												
2023												
2024												
2025												
2026												
2027												
2028												
2029												
2030		20300515H391										
2031												
2032												
2033												
2034												
2035												

3.4.10 Pandora batch process

The event list described in section 3.4.7 is used as input to be processed by Pandora. Figure 3.26 provides an overview of the Pandora batch process applied. The Pandora application relies on mandatory external input files containing information on data projection, weather streams, fuel type mappings, as well as ignition and fuel grids. Grids representing elevation, slope and aspect are optional. Results from Pandora are then exported to a flat file for further statistical analyses.

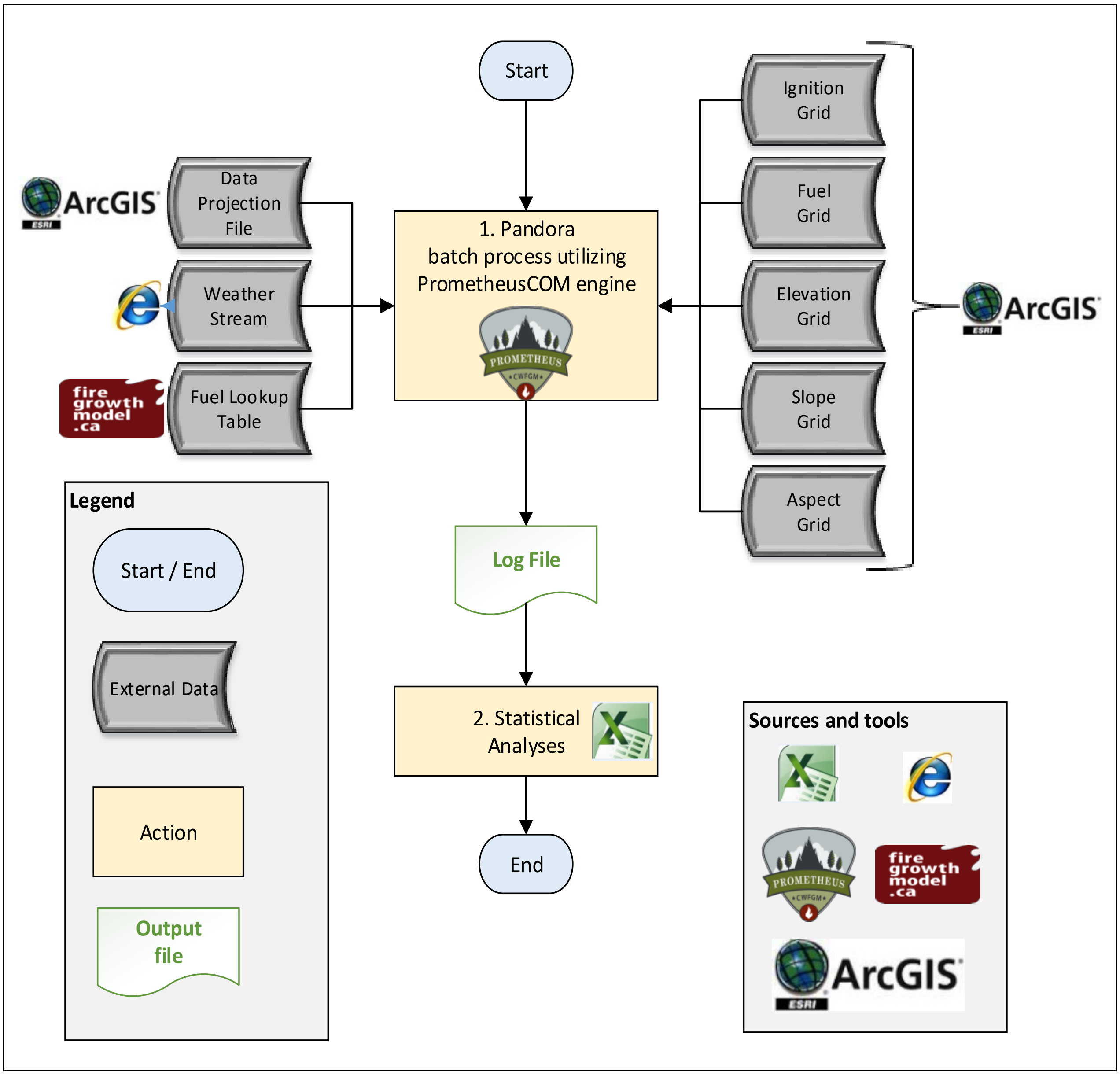


Figure 3.26 Pandora batch process overview

3.5 Summary

In this chapter, methodology, scope and process flows have been described for assessing firebreak strategies in the Southside. The selection logic of historical wildfire data has been presented along with the analyses of these data and derivation of probability density functions of wildfire count, -cause and -size. This serves as a foundation for evaluating existing risk management strategies and deriving opportunities for improvement.

A number of scope limitations have been defined, along with related simplifications and assumptions. The area of study of wildfire occurrence is the Nechako Lakes Electoral District comprised of 7.38 million hectares. The firebreak simulation modelled area is resticted to the 236,659 hectares covering the Southside. The time window of 1 simulation for the baseline scenario as well as each of the firebreak strategies is 10,000 years. Based on various impact analyses of historic data, simulations were applied only from April through September of each year, and only for wildfires with a size of at least 100 hectares. Wildfire cause and weather stream were determined based on historic averages. Wildfire ignitions were applied randomly across 9 of the 18 land use types, with a cell size of 1 hectare. A baseline strategy and a number of fuel treatment or firebreak strategies were simulated to assess their impact on values at risk in terms of area burned and with respect to five macro-economic indicators.

Five firebreak strategies are compared to a baseline scenario with an unchanged land use grid. Each strategy entails the implementation of 100 metre wide firebreaks around areas with values at risk. Private property represents the values at risk in strategy PRIV. In strategies TSA1 (Timber Supply Areas), PROV (Provincial Parks), COMF (Community Forest) and WLOT (Woodlots), firebreaks are placed around the boundaries of these areas as well as around old growth forest within these areas. The null hypothesis that will be tested is that implementing firebreaks around areas with values at risk has no significant impact on average total area annually being burned inside and outside the protected areas.

4. Analysis and Results

In this chapter, simulation results are presented. Section 4.1 covers the simulation results of the baseline scenario and section 4.2 presents the results of each of the five different fuel treatment firebreak strategies. These findings are then compared and evaluated in section 4.3. Results from sensitivity analyses on weather stream parameter settings are presented in section 4.4. A summary is given in section 4.5.

4.1 Baseline (BASE) Strategy

Table 4.1 shows the results for the baseline strategy denoted BASE. The total area burned over 777 successful ignitions over the 10,000-year period in the Southside was 530,626 hectares for the AVG weather-related scenario. The favourable scenario (FAV) in terms of uncontrollable weather conditions leads to an 85% reduction in total burned area relative to the average. Unfavourable weather conditions in scenario UNF lead to an increase in burned area to a level of 344% of the AVG scenario. These results illustrate the significant impact of uncontrollable variables on the overall result.

Table 4.1 Baseline Strategy: Scenario Results

Strategy ↓	Scenario ↓	Area burned	Change
Unit of measure →		ha	%
BASE	UNF	1825305	344%
BASE	AVG	530626	100%
BASE	FAV	81249	15%

4.2 Firebreak Strategies

In this section, different simulation strategies are described in terms of their impact. Table 4.2 presents the effects of firebreaks in each of the five strategies. The total area burned over 777 events across 10,000 independent years was 530626 hectares for the Baseline scenario. All fuel treatment or firebreak strategies lead to a reduction in total area burned. Placing firebreaks around private property in the Southside (PRIV) resulted in a reduction of 89.2% of total private property burned within the protected area, while also leading to a reduction of area burned outside private property boundaries with 19%. The placement of firebreaks around the boundaries of Timber Supply Areas in addition to old forest growth within these areas (TSA1), resulted in a reduction of 76.7% of total TSA burned. It also lead to a reduction of area burned outside TSA boundaries with 55.1%. The pattern of these effects was similar for the other three firebreak strategies in terms of causing a beneficial side effect outside the assets being protected through firebreaks. The PARK, COMF and WLOT strategies lead to a reduction of respectively 81.5%, 60.4% and 93.5% within their boundaries, while also reducing the area burned outside their boundaries with respectively 1.1%, 16.6% and 14.1%. Overall, the TSA1 firebreak covering

10.5% of the landscape leads to the highest reduction in total burned area, namely 69.3% as noted in Table 4.2 below.

Table 4.2 Firebreak Strategies - primary output indicators for the AVG scenario

Strategy ↓	Scenario ↓	Protected asset ↓	Area rel. to fire break	Area (ha)	Fire break size		Total Area (ha) burned annually			
					Ha	%	Without fire breaks	With fire	Area saved	
Unit of measure →			Ha	Ha	Ha	%	ha / year	ha / year	ha / year	%
BASE	**AVG**	N.A.	N.A.	236844	0	0%	53.06	N.A.	N.A.	N.A.
PRIV	**AVG**	Private Property	Total	236844	12748	5.40%	53.06	17.59	35.47	**29.0%**
			Inside	33784	0	0%	7.57	47.33	10.3	89.2%
			Outside	190312	12748	5.40%	45.49	10.08	13.2	19.0%
TSA1	**AVG**	Timber Supply Area	Total	236844	24949	10.50%	53.06	22.68	56.2	**69.3%**
			Inside	155354	0	0%	37.14	40.70	40.8	76.7%
			Outside	56541	24949	10.50%	18.26	29.24	15.4	55.1%
PARK	**AVG**	Provincial Park	Total	236844	1578	0.67%	53.06	22.94	30.12	**3.8%**
			Inside	7854	0	0%	2.54	43.25	2.2	81.5%
			Outside	227412	1578	0.67%	51.30	0.58	0.9	1.1%
COMF	**AVG**	Community Forest	Total	236844	3041	1.28%	53.06	52.52	0.54	**21.3%**
			Inside	25168	0	0%	5.68	32.05	5.2	60.4%
			Outside	208635	3041	1.28%	47.42	8.81	12	16.6%
WLOT	**AVG**	Awarded Woodlot	Total	236844	5257	2.22%	53.06	29.71	23.35	**18.6%**
			Inside	13332	0	0%	3.03	49.61	4.3	93.5%
			Outside	218255	5257	2.22%	50.08	7.48	10.8	14.1%

4.3 Comparison and evaluation of firebreak strategies

In this section, the baseline and alternative firebreak strategies are compared and evaluated.

Table 4.3 summarizes the comparative effectiveness of each of the five firebreak strategies tested, in terms of reduction in burned area per area of firebreak. It also shows the rankings between these strategies. Reduction of area burned per area of firebreak is highest with firebreaks placed around and within community forests (COMF), and lowest with firebreaks placed around private property (PRIV). The highest performance was obtained with the COMF strategy, followed by PARK, WLOT, TSA1 and PRIV. These results are visually presented in Figure 4.1, displaying the performance of each strategy as a percentage of the maximum performance attained in the COMF strategy. The overall performance of each strategy across all scenarios is presented in Figure 4.2. The percentage wise performance of PARK, WLOT, TSA1 and PRIV in comparison to the COMF strategy is respectively 62.4%, 60.6%, 44.5% and 37.2%.

Table 4.3 Comparative performance of Firebreak Strategies

Strategy ↓	Scenario ↓	Without fire breaks	With fire breaks	Change		Performance	Average Performance	Rank
Unit of measure →		Ha	Ha	Ha	%	ha / (km^2 *	ha / (km^2 * year)	
BASE	UNF	1825305	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	AVG	530626	N.A.	N.A.	N.A.	N.A.	N.A.	
	FAV	81249	N.A.	N.A.	N.A.	N.A.	N.A.	
PRIV	UNF	1825305	1245560	-579745	-31.8%	72.19	30.67	5
	AVG	530626	389321	-141305	-26.6%	17.59		
	FAV	81249	63274	-17975	-22.1%	2.24		
TSA1	UNF	1825305	496889	-1328416	-72.8%	84.52	36.67	4
	AVG	530626	174118	-356508	-67.2%	22.68		
	FAV	81249	36910	-44339	-54.6%	2.82		
PARK	UNF	1825305	1697934	-127371	-7.0%	128.12	51.47	2
	AVG	530626	507817	-22809	-4.3%	22.94		
	FAV	81249	77911	-3338	-4.1%	3.36		
COMF	UNF	1825305	1462600	-362705	-19.9%	189.32	82.44	1
	AVG	530626	430005	-100621	-19.0%	52.52		
	FAV	81249	70739	-10510	-12.9%	5.49		
WLOT	UNF	1825305	1438264	-387041	-21.2%	116.86	49.98	3
	AVG	530626	432214	-98412	-18.5%	29.71		
	FAV	81249	70107	-11142	-13.7%	3.36		

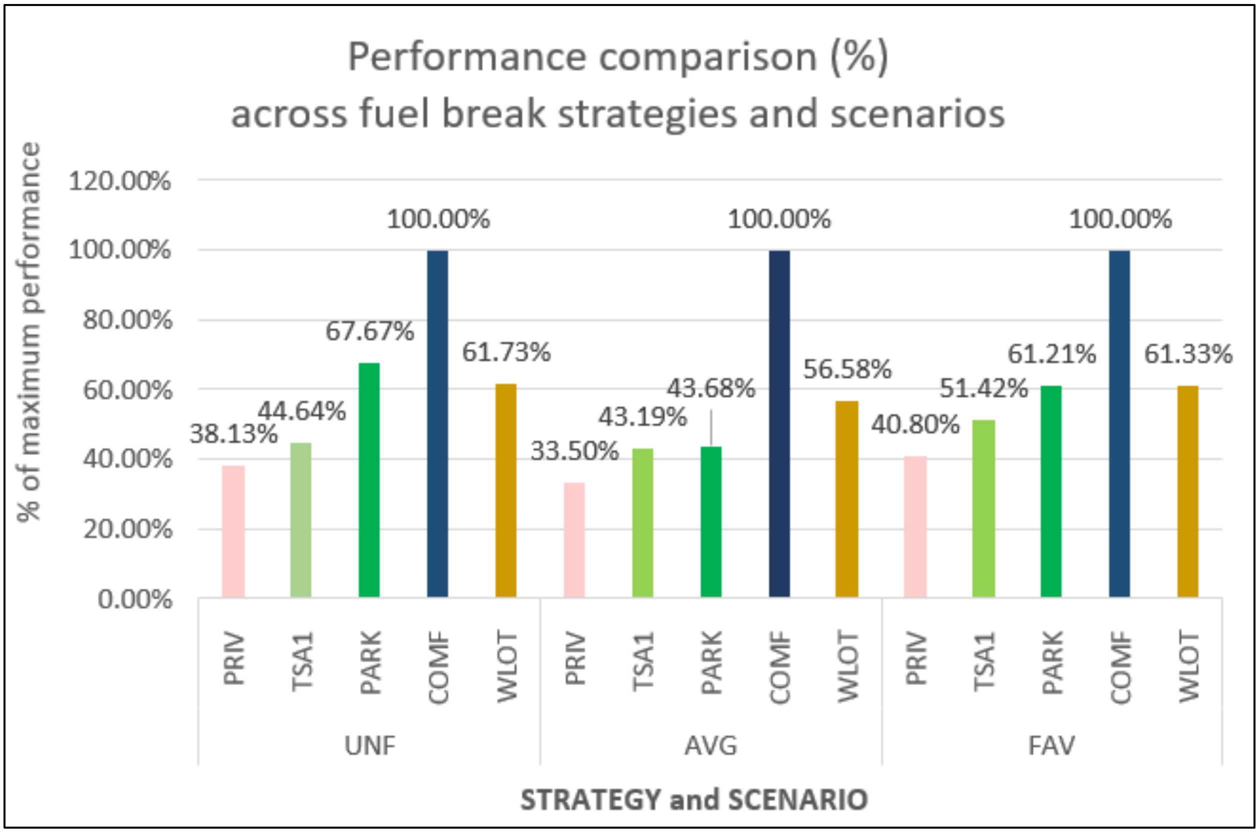


Figure 4.1 Performance comparison by firebreak strategy and scenario

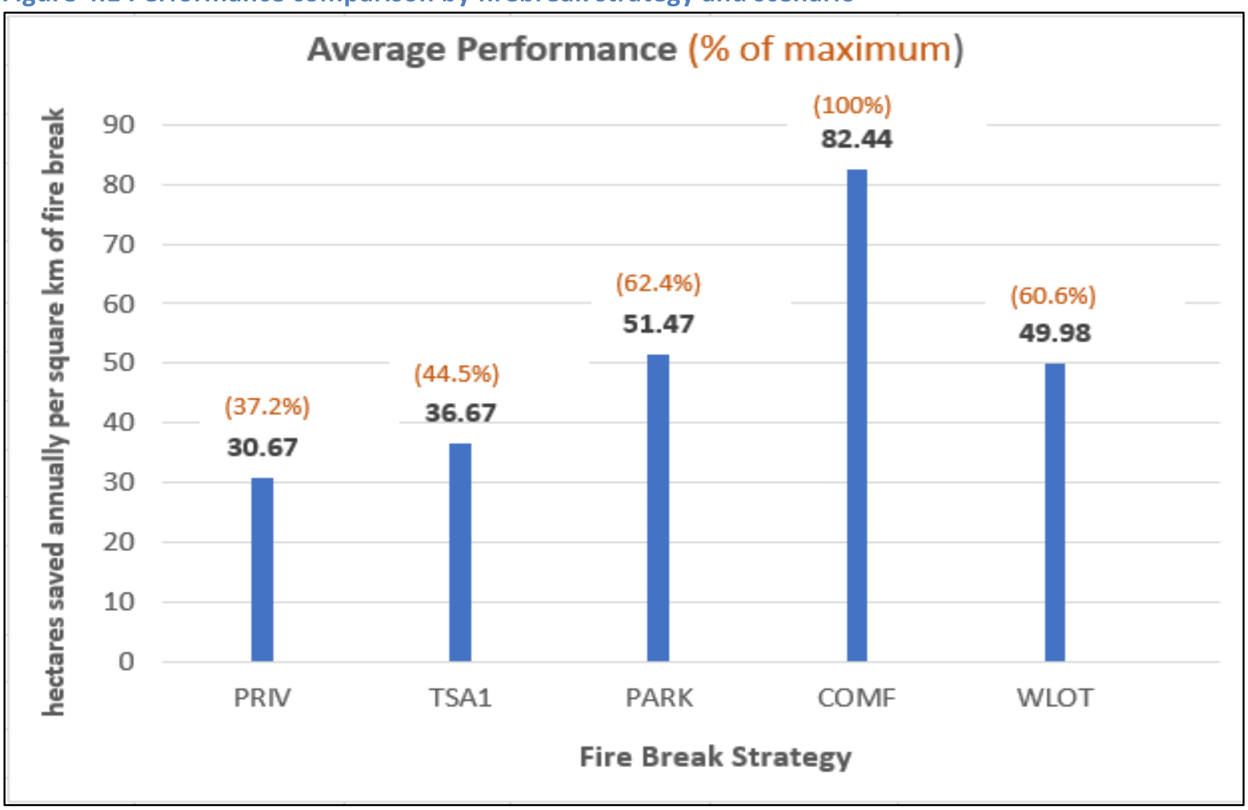


Figure 4.2 Comparative overall performance by firebreak strategy across all scenarios

Key performance indicators are presented in Table 4.4. Scenario UNF leads to the highest reductions in area burned. Favourable weather conditions represented in scenario FAV lead to the lowest reductions, which are significantly below those in average weather conditions. A similar pattern is observed for the other performance indicators. The overall effect of each of the firebreak strategies is therefore expected to be strongest in unfavourable weather conditions and the best results are obtained for the COMF strategy.

Table 4.4 Key performance indicators, extrapolated to the Nadina Forest District

Strategy ↓	Scenario ↓	key performance indicators (annual impact per square km of fire break)							Rank
		Reduction in area burned	Additional Gross Revenue	Additional Net Regional Product	Additional Royalties and indirect taxes	Additional Gross wages	Additional Employment positions	Firefighting cost savings (million $)	
Unit of measure →		ha / (km^{-2} * year)	CAN $	CAN $	CAN $	CAN $	persons	CAN $	
BASE	UNF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	N.A.
PRIV	UNF	72.19	924180	547851	181889	278291	0.0441	2530.76	5
TSA1	UNF	84.52	1082039	641429	212958	325825	0.0516	2963.03	4
PARK	UNF	128.12	1640308	972369	322832	493932	0.0782	4491.79	2
COMF	UNF	189.32	2423812	1436828	477034	729863	0.1155	6637.32	1
WLOT	UNF	116.86	1496169	886924	294464	450529	0.0713	4097.08	3
BASE	AVG	0.0	0	0	0	0	0.0000	0.0	N.A.
PRIV	AVG	17.59	225256	133531	44333	67830	0.0107	616.84	5
TSA1	AVG	22.68	290388	172141	57152	87442	0.0138	795.19	4
PARK	AVG	22.94	293739	174127	57811	88451	0.0140	804.37	3
COMF	AVG	52.52	672410	398602	132338	202477	0.0321	1841.31	1
WLOT	AVG	29.71	380427	225516	74873	114555	0.0181	1041.75	2
BASE	FAV	0.0	0	0	0	0	0.0000	0.0	N.A.
PRIV	FAV	2.238	28654	16986	5639	8628	0.0014	78.47	5
TSA1	FAV	2.821	36116	21409	7108	10875	0.0017	98.90	4
PARK	FAV	3.358	42987	25483	8460	12944	0.0020	117.72	3
COMF	FAV	5.486	70234	41635	13823	21149	0.0033	192.33	1
WLOT	FAV	3.364	43071	25532	8477	12970	0.0021	117.95	2

4.4 Sensitivity Analysis

Parameter settings for each of the uncontrollable variables in this study are specified in Table 4.5 as part of sensitivity analysis to clarify the effect of changing parameter values on the output values.

Table 4.5 Sensitivity Analysis for uncontrollable parameters in the BASE strategy

Scenario	Month	Parameter setting							
		Temp.		Relative humidity	Precipi-tation	Wind speed		Wind direction	Wildfire count
		Min	Max			Min	Max		λ (event rate)
		°C	°C	%	mm	km/h	km/h	°	100+ ha fires/month
Cold	April	-4.3	7.9	62.80	0.79	0.83	61	135	0.00255
	May	-0.1	13	62.65	1.23	0.85	51	0	0.01528
	June	3.5	16	66.15	1.84	0.63	57	0	0.01019
	July	5.6	19	69.35	1.47	0.54	50	0	0.027
	August	4.9	18	70.70	1.46	0.48	46	0	0.01885
	September	1	13	74.85	0.79	0.36	56	135	0.00815
Warm	April	1.7	14	62.80	0.79	0.83	61	135	0.00255
	May	5.9	19	62.65	1.23	0.85	51	0	0.01528
	June	9.5	22	66.15	1.84	0.63	57	0	0.01019
	July	12	25	69.35	1.47	0.54	50	0	0.027
	August	11	24	70.70	1.46	0.48	46	0	0.01885
	September	7	19	74.85	0.79	0.36	56	135	0.00815
Wet	April	-1.3	11	75.36	0.95	0.83	61	135	0.00255
	May	2.9	16	75.18	1.47	0.85	51	0	0.01528
	June	6.5	19	79.38	2.21	0.63	57	0	0.01019
	July	8.6	22	83.22	1.76	0.54	50	0	0.027
	August	7.9	21	84.84	1.75	0.48	46	0	0.01885
	September	4	16	89.82	0.95	0.36	56	135	0.00815
Dry	April	-1.3	11	52.33	0.66	0.83	61	135	0.00255
	May	2.9	16	52.21	1.02	0.85	51	0	0.01528
	June	6.5	19	55.13	1.53	0.63	57	0	0.01019
	July	8.6	22	57.79	1.23	0.54	50	0	0.027
	August	7.9	21	58.92	1.22	0.48	46	0	0.01885
	September	4	16	62.38	0.66	0.36	56	135	0.00815
Windy	April	-1.3	11	62.80	0.79	0.99	73.2	135	0.00255
	May	2.9	16	62.65	1.23	1.02	61.2	0	0.01528
	June	6.5	19	66.15	1.84	0.76	68.4	0	0.01019
	July	8.6	22	69.35	1.47	0.65	60	0	0.027
	August	7.9	21	70.70	1.46	0.58	55.2	0	0.01885
	September	4	16	74.85	0.79	0.43	67.2	135	0.00815
Windstill	April	-1.3	11	62.80	0.79	0.69	50.8	135	0.00255
	May	2.9	16	62.65	1.23	0.71	42.5	0	0.01528
	June	6.5	19	66.15	1.84	0.53	47.5	0	0.01019
	July	8.6	22	69.35	1.47	0.45	41.7	0	0.027
	August	7.9	21	70.70	1.46	0.40	38.3	0	0.01885
	September	4	16	74.85	0.79	0.30	46.7	135	0.00815

Uncontrollable weather related parameters used in sensitivity analysis (continued)

Scenario	Month	Parameter setting							
		Temp.		Relative humidity	Precipi-tation	Wind speed		Wind direction	Wildfire count
		Min	Max			Min	Max		λ (event rate)
		°C	°C	%	mm	km/h	km/h	°	100+ ha fires/month
North	April	-1.3	11	62.80	0.79	0.83	61	0	0.00255
	May	2.9	16	62.65	1.23	0.85	51	0	0.01528
	June	6.5	19	66.15	1.84	0.63	57	0	0.01019
	July	8.6	22	69.35	1.47	0.54	50	0	0.027
	August	7.9	21	70.70	1.46	0.48	46	0	0.01885
	September	4	16	74.85	0.79	0.36	56	0	0.00815
East	April	-1.3	11	62.80	0.79	0.83	61	90	0.00255
	May	2.9	16	62.65	1.23	0.85	51	90	0.01528
	June	6.5	19	66.15	1.84	0.63	57	90	0.01019
	July	8.6	22	69.35	1.47	0.54	50	90	0.027
	August	7.9	21	70.70	1.46	0.48	46	90	0.01885
	September	4	16	74.85	0.79	0.36	56	90	0.00815
South	April	-1.3	11	62.80	0.79	0.83	61	180	0.00255
	May	2.9	16	62.65	1.23	0.85	51	180	0.01528
	June	6.5	19	66.15	1.84	0.63	57	180	0.01019
	July	8.6	22	69.35	1.47	0.54	50	180	0.027
	August	7.9	21	70.70	1.46	0.48	46	180	0.01885
	September	4	16	74.85	0.79	0.36	56	180	0.00815
West	April	-1.3	11	62.80	0.79	0.83	61	270	0.00255
	May	2.9	16	62.65	1.23	0.85	51	270	0.01528
	June	6.5	19	66.15	1.84	0.63	57	270	0.01019
	July	8.6	22	69.35	1.47	0.54	50	270	0.027
	August	7.9	21	70.70	1.46	0.48	46	270	0.01885
	September	4	16	74.85	0.79	0.36	56	270	0.00815

Results from section 4.1 have shown that when dry, warm and windy parameter settings are combined in scenario UNF, this leads to an increase in burned area to a level of 344% of the AVG scenario. Table 4.6 presents the results of sensitivity analyses of weather stream parameters of the BASE scenario. This shows that large impacts on model performance originate from the defined fluctuations in wind direction, humidity and precipitation. The influence of a variation in temperature (3 degrees in our test) is also significant in the model's output. The lowest impact in model output was caused by the set 20% variation in wind speed. Note that the topography of the Southside is characterized by consistent east-west mountain slopes and valleys. This explains the large impact of wind direction on model output.

Table 4.6 Sensitivity Analysis of weather stream parameters in the BASE strategy

Parameter setting	Total area burned (ha)		
	Total area burned (ha)	Change (ha)	Change (%)
As per BASE strategy	530626	0	0
COLD	406149	-124477	-23.46%
WARM	651859	121233	22.85%
WET	281840	-248786	-46.89%
DRY	746911	216285	40.76%
WINDY	554411	23785	4.48%
WINDSTILL	461129	-69497	-13.10%
NORTH	528282	-2344	-0.44%
EAST	832185	301559	56.83%
SOUTH	533898	3272	0.62%
WEST	808460	277834	52.36%

4.5 Summary

In this chapter, the effect of placing firebreaks around and within the boundaries of assets to be protected was reported and evaluated. The total area burned over 777 successful ignitions during 10,000 years in the Southside was 530626 hectares for the average weather stream scenario.

All firebreak strategies lead to a reduction of total area burned. Placing firebreaks around private property in the Southside resulted in a reduction of 89.2% of total private property burned, while also leading to a reduction of area burned outside private property boundaries with 19%. The placement of firebreaks around the boundaries of Timber Supply Areas in addition to old forest growth within these areas resulted in a reduction of 76.7% of total TSA burned. It also lead to a reduction of area burned outside TSA boundaries with 55.1%. The pattern of these effects was similar for the other three firebreak strategies in terms of causing a beneficial side effect outside the assets being protected through firebreaks. The PARK, COMF and WLOT strategies lead to a reduction of respectively 81.5%, 60.4% and 93.5% within their boundaries, while also reducing the area burned outside their boundaries with respectively 1.1%, 16.6% and 14.1% (see Table 4.2).

The performance of firebreaks in the Southside measured in terms of reductions of area burned per area of firebreak is highest with firebreaks placed around and within community forests and lowest with firebreaks placed around private property. The percentage wise overall performance of the PARK, WLOT, TSA1 and PRIV strategies in comparison to the COMF strategy is respectively 62.4%, 60.6%, 44.5% and 37.2% (see Figure 4.2). Although this has not been investigated further, the variation in performance is possibly caused by the combination of firebreak direction and topographical aspects. These results can therefore not be extrapolated beyond the simulated area, but do give an indication of the performance variation that may be expected when similar firebreaks are applied elsewhere.

Model performance of all firebreak strategies is heavily and consistently influenced by weather stream parameters. Sensitivity analyses of weather stream parameters show that although the reduction in total area burned varies, the ranking between strategies in their overall performance is consistent regardless of the weather pattern. Combined dry, warm and windy weather conditions in the UNF model scenario lead to a factorial increase of 3.44 in total area burned as compared to the average weather conditions as defined in the AVG scenario. With favourable weather conditions represented by wet, cold and low wind conditions in the FAV scenario the model shows an 85% reduction in total burned area as compared to the AVG scenario. These results illustrate the significant impact of uncontrollable variables on the overall result.

5. Discussion

In this chapter, the applied methodology and obtained results reported in the previous chapters are evaluated and compared with similar efforts reported from in the literature. Limitations and opportunities for improvement are also discussed.

5.1 Use of historic data

A number of studies have explored probability distributions of wildfire characteristics over longer periods of time (Holmes et al, 2007; Moll, 1991; Moll, 1992; Preisler et al, 2004). In our model, probability density functions were derived using historic data obtained from the Nechako Lakes Electoral District. The underlying limitation of this approach is that any changes in land use throughout the period from 1950-2012 were not linked with changes in wildfire events, since only the most recent land use and land ownership maps were utilized. Land uses such as 'selectively logged', 'recently burned' 'young forest' and 'old forest' represent snapshots in time. Land ownership could have changed at least once within this 63-year period as well. The predictive power of using density functions of wildfire count, -cause and -size when using these historic data for impact assessment is thus limited. Structural or temporary shifts in land use or land ownership may well have been caused by the occurrence of wildfires themselves.

5.2 Model calibration

The following four notions are made with respect to parameter estimation.

5.2.1 Wildfire Count

The first notion is regarding wildfire count. The overall best-fitting probability density function or the parameter 'wildfire count' was given with the Poisson distribution. This discrete distribution with memoryless properties has been used successfully elsewhere to describe fire starts (Green, 1989; Harrington and Donnelly, 1978). The lambda value of the Poisson distribution function for the Southside was derived by its surface in proportion to the surface of the Nechako Lakes Electoral District. The simplification made here was that the distribution would be exactly proportional to land surface. Another simplification is that all wildfires occurred independently without interference. Prometheus can simulate multiple fires but not their interactions. Table 3.30 showed an example of an event list for a 20-year window. Given the low lambda value of the distribution, the time between wildfires on average was such that wildfires hardly occurred simultaneously and if they did, the probability that they lead to overlapping areas being burned was minimal as well.

5.2.2 Wildfire Duration

Secondly, for the calibration of wildfire duration versus time in Pandora, the equation mentioned in section 3.12 was used to derive wildfire duration from wildfire size. Pandora only processes information on an hourly basis. Therefore, in the input file the value of Y had to be rounded off to the closest integer. This introduces variation that affects the outcome of each simulation in terms of total area burned.

5.2.3 Planned versus Actual Wildfire Count and Size

The third notion is regarding the discrepancy between planned and actual wildfire count and -size. In the 10,000-year simulation window, not all ignitions lead to a wildfire in Prometheus and the end result consisted of only 777 successful ignitions. As a result of the calibration between wildfire duration and –size, there was a large variability of the difference between actual and planned wildfire sizes. However, this does not hamper impact assessment since the performance rankings remain the same.

5.2.4 Fuel Types

The fourth and final notion made here is regarding fuel types. Prometheus requires fuel types among the inputs. As part of our source data, only land types were available for the Southside. This mandated a mapping exercise by allocating land use and fuel type, the result of which was presented in Table 3.28. Although this is a fairly significant simplification of reality, it must be stated that this allocation was applied consistently for all firebreak strategies. However, if a more refined set of polygons with a more diversified mosaic of fuel types would have been available, it could have affected the outcome to the extent that the performance ranking would have been different between the five firebreak strategies. A similar argument can be made for topographic aspects beyond the Southside, which is the topic of the following section.

5.3 Model scaling

Development and application of the simulation model in this thesis took place at three distinct levels. Firstly, data collection took place at the level of the Nechako Lakes Electoral District ensuring that a sufficiently large data set was available for reliable estimates. To this end, the national fire database served as a historical reference deriving the predictive factors to be applied in the simulation modelling cycles of the wildfire model. Secondly, the Nadina Natural Resource District, the largest area within the Nechako Lakes Electoral District and covering 40.5% of its total surface, was the area for comparing firebreak strategies with existing management strategies. The main motivation for looking at the Forest District level was to be able to evaluate firebreak strategies with reference to existing macro-economic studies and policies at this level. Thirdly, the Southside, within the Nadina Forest District, was the area where the developed wildfire simulations were applied in this research. It was selected as a sub-set of the Nadina Forest District to enable simulations yielding reliable output and requiring cell resolutions between 30 and 100 metres (Perrakis, 2016; Strimbu, 2015; Tymstra et al, 2010). Because of unique topographic characteristics of each area, model parameter estimates and therefore also simulation results ideally should not be extrapolated to Nadina *per se*. Rather, the intent of bringing the results up one level to the Nadina Forest District was to illustrate the order of magnitude of macro-economic output indicators. For strategy and scenario evaluations to be compared reliably, both parameter estimates and simulations should have been applied to the Nadina Forest District in its entirety. As explained, the model had to be scaled up based on data volume requirements for reliable parameter estimates, while the scaling down was based on simulation accuracy requirements. This research carried out in the Southside however enabled us to at least demonstrate methodology and process steps required to obtain and evaluate simulation results.

5.4 Breaching and spotting

In the Canadian Forest Fire Danger Rating System, components of the fire behaviour triangle (fuel, weather and topography, see also Figure 2.1) constitute inputs controlling fire behaviour. Various terms are used to describe this behaviour. These include smouldering, creeping, running, torching, spotting, crowning and breaching, all of which represent quantitative predictions of fire movement. **Fire breaching** of nonfuel areas occurs when a natural or man-made barrier (e.g., lake, river, road, etc.) fails to stop the advancing fire front (Tymstra et al, 2010). This may be caused by ember transport, direct flame contact, thermal radiation or fire whirls (Countryman 1971; Wilson 1988). **Fire spotting** is defined as the phenomenon in which a wildfire produces fire brands (embers) carried by the wind, a fire whirl, and/or convection column that fall beyond the main fire perimeter and result in spot fires (Saskatchewan Environment, 2005).

The Prometheus model has incorporated breaching and spotting functions (Alexander et al, 2004; Tymstra et al, 2010). However, when running the Prometheus-engine through Pandora, the setting to adjust the perimeter for fuelbreaks and landscape boundaries is not activated. This is compensated using FBP fuel types of all other areas with spread rate equations that are designed to take spotting into account. So, while there was no spotting as part of the simulations, the spread rate in continuous fuels includes spotting. Our model works on the premise that the 100 metre firebreaks are 100% effective and no breaching or spotting occurs. When a fire vertex reaches a fuelbreak, this vertex is then marked as inactive and the fire is stopped. In reality however, 100-meter firebreaks applied to the landscape are generally sufficient to stop breaching, but not spotting. It is through spotting that structures in most actual interface fires are ignited, including those in Kelowna, Slave Lake and Fort McMurray. For example, a fire intense enough to breach even a 100-meter break would also be intense enough to spot across it and more. To illustrate this point, Figure 5.1 displays a photo of the fireguard constructed between Okanagan Mountain Park and the city of Kelowna in 2003. With extreme conditions during the firestorm in that year the fire spotted across rapidly and kept on going (Englefield, 2016). By defining fuelbreaks as nonfuel areas in the fuel grids for each strategy in combination with the deactivation of the Prometheus-setting to adjust the perimeter for fuel breaches and using FBP fuel types with increased spread rate equations, our model simulations therefore are expected to yield reliable estimates of area burned.

Figure 5.1 Firebreak between Okanagan Mountain Park and City of Kelowna in 2003
Source: BC Wildfire Services, 2016.

5.5 Ranking Procedure and Decision Support

Performance ranking resulting from the comparison of firebreak strategies in our model should be merely one aspect in the decision making process for wildfire risk mitigation at a landscape level. Our key performance indicators and output variables were derived from the area burned, applying 2005-dollar values obtained from only one study (Patriquin et al, 2005). Furthermore, a set of short- and long-term costs and benefits of creating firebreaks beyond the primary and secondary output variables is not considered in this thesis, nor are the firebreak strategies compared to other fuel treatment strategies. Developing firebreak strategies using decision support methodology requires a comprehensive assessment of values at risk, including but not limited to recreational, cultural and socio-economic values. Numerous optimization models, systems dynamics models and operational research methods have been developed to assist in addressing complex spatial optimization problems and in making landscape-level fuel treatment decisions (Minas, 2013; Martell, 2011). In the case of the Nadina Forest District, such decision support tools should be explored further to assist in making landscape changes required to mitigate wildfire risks. The outcomes presented here can be employed in developing and improving existing strategies.

5.6 Policy Implications

Firebreaks and other wildfire fuel treatments have been implemented widely by numerous communities across British Columbia as part of the Strategic Wildfire Prevention Initiative (Forest Practices Board, 2015ab). Unfortunately, still only about 10 percent of high risk forests around communities have received a fuel management treatment over the past decade. Funding to protect at-risk communities in BC by removing interface fuel sources has been reported as inadequate, with estimated fuel treatment costs of up to $10,000 per hectare. The adoption of FireSmart principles by residents in at-risk communities has been minimal, partly due to the lack of incentives for landowners to treat hazardous fuels on their property (Forest Board Practices, 2015b).

An important assumption in designing the strategies of our model is that the loss of vegetation resulting from implementing firebreaks can be offset with and financed by an increased availability of harvestable timber on a continuous basis. A Business Case by the BC Wildfire Management Branch in 2014 illustrated that the ratio of return on investment for fuel reduction treatment benefits for high risk stands compared to treatment costs can be calculated was 3.4:1. It was stated that this ratio could be significantly higher if numerous other benefits such as positive impacts on water quality, erosion levels and habitat would be quantified and included in the analysis (MLNFRO, 2014). In terms of relevance for our study, it must be stated that the business case was defined in a wildland urban interface in close proximity to a densely populated area. With significantly lower asset values, remote and rural communities in the wildland urban interface in the Nadina Forest District are far from guaranteed to receive the same level of emergency response as compared to their counterparts in more densely populated areas where the stakes for the economy can be ultra-high as shown during the Fort McMurray wildfires recently. We are thus faced with practical challenges of priority determination in policy design. A prerequisite for proper allocation of government funding and priority setting is a common understanding of comparative numeric and socio-economic values of different elements of the landscape. This requires continued debate involving all stakeholders in the community to establish timely, fair and just execution of policy.

5.7 Summary

In the above, the most prevalent model limitations were presented in terms of data availability, model calibration and –scaling, ranking procedure, decision support and policy implications. The next chapter presents conclusions and recommendations from this work.

6. Conclusions and Recommendations

This thesis has presented a data-driven approach for the assessment of rural communities' vulnerability to wildfires and presented a methodology to design, simulate and compare firebreak strategies.

6.1 Conclusions

The first research question in this thesis was: "**what are the vulnerabilities of remote rural communities in the Nechako Lakes Electoral District in BC to wildfires**?" The review in this thesis has clarified that British Columbia has entered an era of increased frequency and severity of wildfires due to past fire suppression regimes and current climatological pressures which have contributed to the mountain pine beetle infestation. This has partially been addressed with temporary increases by BC's Ministry of Forests, Lands and Natural Resources Operations of Allowable Annual Cuts issued to Timber Supply Areas including those in the Nechako Lakes Electoral District. Nevertheless, substantial risks remain of catastrophic wildfires directly jeopardizing rural communities and the various privately, corporately or communally owned assets. Especially in recent years, fire hazards and damages have been steadily on the rise across the entire area and without further measures, this area will continue to be exposed to high risks of wildfire in the upcoming period.

The second research question was: "**Which fuel management strategies are currently used in protecting these communities from wildfires**?" Wildfire Fuel Management can be categorized as fuel reduction, fuel conversion, fuel isolation or fragmentation. In the Forest Districts covered by the Nechako Lakes District, all these strategies are applied either by government, industry or property owners. Important initiatives in this regard include the FireSmart program, woodlot management, parks management and the management of timber supply areas. Fuel loads are reduced by using periodic prescribed burns or thinning practices. Highly flammable coniferous fuels are replaced with less flammable deciduous fuel, harvesting and/or prescribed burning followed by planting deciduous species. Fuels are also isolated by fragmenting them through the use of roads, cut blocks and firebreaks, thereby reducing the vertical and horizontal continuity of flammable fuels.

The third research question was "**How can firebreaks be applied in protecting remote rural communities within this area?"** The results in this thesis show that firebreaks are effective in significantly reducing the area burned in different parts of the landscape within the Southside. The performance of different strategies shows large variation. Although this has not been investigated further, sensitivity analyses seem to indicate that this variation is likely being caused by topographic aspects and the positioning of firebreaks in the landscape in relation to climatic parameters. These results can therefore not be extrapolated beyond the simulated area, but do give an indication of the performance variation that may be expected when similar firebreaks are applied elsewhere. Topography of the Nechako Lakes District and the larger Montane Cordillera Ecozone is highly diverse. Local vulnerability of rural communities to wildfire when assessed using similar simulation exercises, is therefore expected to also show large variations.

In this thesis, statistical analyses and simulation modelling tools have been effectively used to obtain insight in expected results from firebreaks when applied to different parts in the landscape. The next section will elaborate on recommendations and future research.

6.2 Recommendations

The outcome of this research only underlines the potential of implementing firebreaks. It is only one of the many tools available to provincial and local governments, forest industry and private landowners to protect communities. Given the current trends in wildfire events in western Canada, intensification of efforts on all fronts is required. This should include the following:

- Education of all stakeholders on their respective roles and responsibilities;
- Increased funding for simulation modelling research, cost-benefit analysis and landscape redesign;
- Accelerated rollout of localized wildfire fuel treatments across the province.

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Appendix A. Land Ownership and Schedule Codes

Sources: www.bcstats.gov.ca, www.data.gov.bc.ca, www.geobase.ca

The ownership coverage is a subset of the data from Tantalis. Ownership A code indicating the ownership and administrative responsibility for the land contained within the polygon. The major classes of ownership and administrative responsibility include:

- Crown Grants – Private administration (codes in the 40's series);
- Federal Lands – Federal administration (codes in the 50's series);
- Crown Lands – Provincial administration (codes in the 60's series);
- Crown and Private Lands – Private and/or Provincial administration (codes in the 70's series);
- Crown and Private Lands – Local Administration (Codes in the 80's series);
- Crown Lands – Provincial administration under active lease or permit (codes in the 90's series)

Used in conjunction with Ownership Schedule to determine the land that contributes to the Forest Land Base (see under Schedule).
Content: 2 character numeric code for ownership

Permitted Values:
40 Private – Crown Grant 41 Treaty Land 50 Federal Reserve 51 National Park 52 Indian Reserve 53 Military Reserve 54 Dominion Government Block 60 Crown Ecological Reserve 61 Crown UREP (Use, Recreation and Enjoyment of the Public) Reserves 62 Crown Forest Management Unit (TSA) or Crown Timber Agreement Lands 63 Crown Provincial Park Class A 67 Crown Provincial Park equivalent or Reserve 68 Crown BMTA (Biodiversity, Mining and Tourism Area) 69 Crown Miscellaneous Reserves 70 Crown Active Timber Licence in a TSA or TFL 72 Crown and Private Schedule "A" and "B" Lands 74 Crown and Private timber alienated in watershed 75 Crown Christmas tree permit 77 Crown and Private Woodlot Licence 79 Community Forest 99 Crown Misc. lease (Fairground, R&G Club site, recreation cottage site)

Schedule A code indicates whether or not a given area is available for long-term integrated resource management. Use in conjunction with Ownership code to determine land that contributes to the forest land base. Content: 1 character alpha code designating availability of land for long term integrated resource management.
Permitted Values

- A Schedule "A" land – Tree Farm Licence
- B Schedule "B" land – Tree Farm Licence (Crown Land)
- C Land available for long-term integrated resource management
- N Land not available for long-term integrated resource management

Crown Grants – Private Administration

- 40 series: Crown grants obtained by purchase, pre-emption, or lease to purchase regardless of period. This series includes Crown-granted mineral claims where the timber is alienated, and agricultural, industrial leases, which can be purchased and lost to long-term forest and range management.
- 40N: Private – Crown grants
- 41N: Treaty Land, Status Transfer Land

Federal Lands – Federal Administration

50 series: Federal land administered by the Government of Canada. Reserves may range in size from small microwave sites (Transport Canada) to large National Parks.

- 50-N: Federal Reserves
- 51-N: National Parks
- 52-N: Indian Reserves
- 53-N: Military Reserves
- 54-N: Dominion Government Block

Crown Lands – Provincial Administration

60 series: Crown land administered by the Government of British Columbia other than active leases or permits. This series covers all unencumbered Crown lands, surveyed and unsurveyed, including: proposed or planned (unofficial) tenures, ownership reversions, and inactive (reverted) old temporary tenures in whole or in part (Timber Licences, Timber Leases, Pulp Licences, and Pulp Leases).

- 60-N: Crown – Ecological Reserves
- 61 - Crown (N<100ha>C) – UREP (Use, Recreation and Enjoyment of the Public) Reserves
- 62-C: Crown – Forest Management unit (TSA)
- 63-N: Crown – Provincial Park Class A
- 67-N: Crown – Provincial Park equivalent or reserve; Regional Parks, Purcell Wilderness Conservancy, Recreation Areas; Provincial Heritages Sites, Wildlife Management Reserves (single use – name and Order-in-Council, for example, Creston Valley Wildlife Management Area OIC 2657/64), Protected Area Strategy Areas.
- 68N: Crown – BMTS (Biodiversity, Mining and Tourism Area)
- 69 - Crown (N<100ha>C) Miscellaneous reserves, with or without O.I.C.s: • Forest Service Recreation Reserve/Corridor (not including Forest Recreation Trails)
- 2012-09-06 4
- Watershed Reserve • Map Reserve (e.g. Environmental Protection/Conservation) • Fish and Wildlife Management Reserves • Interpretive Forests (N<1000ha>C) unless excluded from Forest
- 90 series: Crown land administered by the Government of British Columbia under active lease and permits.

- 99 - Crown (N<100ha>C) – Miscellaneous leases: • Fairgrounds • Rod and Gun Club sites • Recreational Cottage Site Leases • Community Organization Leases

Crown and Private Lands – Private Administration and / or Provincial Administration

- 70 series: Crown lands administered privately, provincially, jointly, or by other governing bodies, usually in the form of licences having a specified term.
- 70-N: Crown – active timber licence in a TSA
- 70-C: Crown – active timber licence in a TFL
- 72-A: Private – Schedule 'A' land, TFL, where ownership status complete (Land titled to TFL holder).
- 72-B: Crown – Schedule 'B' land, TFL, where ownership status complete
- 74-N: Crown and private – timber alienated in watershed (Greater Vancouver Water District or Greater Victoria Water District only).
- 75-N: Crown – Christmas tree permits)
- 77-N: Crown – Awarded Woodlot licence (Schedule 'B' land. Private portion, Schedule 'A', is coded 40-N).
- 79-B: Community Forest

Appendix B. Prometheus File Formats and GIS Compatibility

Source: www.firegrowthmodel.ca

Prometheus utilizes the open source Geospatial Data Abstraction Library (GDAL) for reading and writing raster data formats and the open source OGR simple features library for reading and writing vector data formats. The following table categorizes Prometheus data input files as required and optional.

Input Element	File Type	Extension	Special Description
Required			
FBP Fuel Type Raster	ASCII raster file	*.asc	ESRI Standard
FBP Fuel Type Lookup Table	Text file	*.lut	Comma Delimited
Projection File	Text file	*.prj	ESRI Standard
Weather Stream	Text file,	*.txt	Delimited
	CSV	*.csv	Comma Delimited
Fire Ignition	Shapefile,	*.shp	ESRI Standard
	Generate file,	*.gen	ESRI Standard
	MapInfo,	*.tab	MapInfo Standard
	KML,	*.kml	Google Earth XML
	KMZ	*.kmz	Google Earth XML (zipped)
Optional			
Landscape Rasters	ASCII raster file	*.asc	ESRI Standard
Wind Speed	ASCII raster file	*.asc	ESRI Standard
Wind Direction	ASCII raster file	*.asc	ESRI Standard
Reference Features	Shapefile	*.shp	ESRI Standard
	Generate file,	*.gen	ESRI Standard
	MapInfo,	*.tab	MapInfo Standard
	KML,	*.kml	Google Earth XML
	KMZ	*.kmz	Google Earth XML (zipped)
Firebreak Features	Shapefile,	*.shp	ESRI Standard
	Generate file,	*.gen	ESRI Standard
	MapInfo,	*.tab	MapInfo Standard
	KML,	*.kml	Google Earth XML
	KMZ	*.kmz	Google Earth XML (zipped)

Fuel and Weather Patches	Shapefile,	*.shp	ESRI Standard
	Generate file,	*.gen	ESRI Standard
	MapInfo,	*.tab	MapInfo Standard
	KML,	*.kml	Google Earth XML
	KMZ	*.kmz	Google Earth XML (zipped)

Prometheus uses two sets of elliptical growth equations to mathematically expand the elliptical wave front: the two-dimensional differential equations of Richards (1990) for flat ground, and the three-dimensional equations defined by Richards (1999) to simulate fire growth where terrain effects are present. The underlying template used to shape fire growth is the simple ellipse model of Van Wagner (1969).

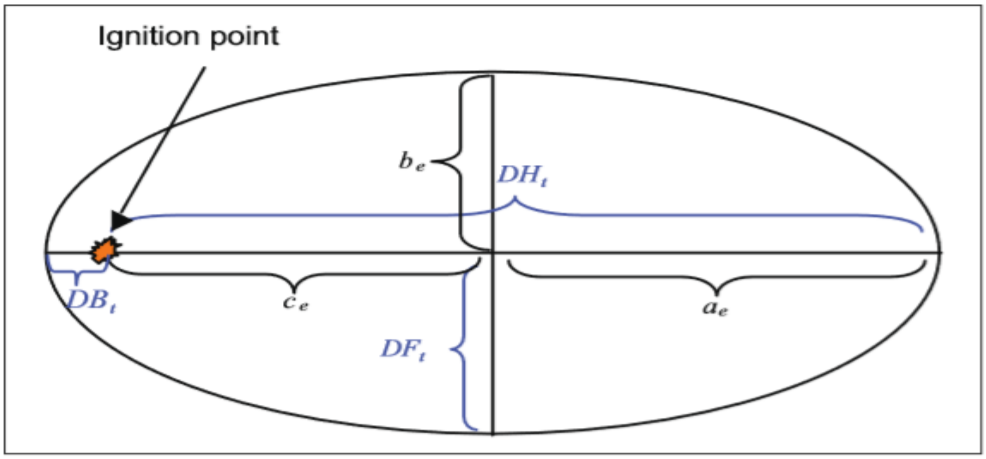

Figure 1. **Dimensions for a simple elliptical fire growth model.** DH_t = head fire spread distance at elapsed time t, DB_t = back fire spread distance at time t, DF_t = flank fire spread distance at time t, a_e = forward spread distance from the center of the ellipse, b_e = flank spread distance, c_e = forward spread distance from the ignition point to the center of the ellipse.

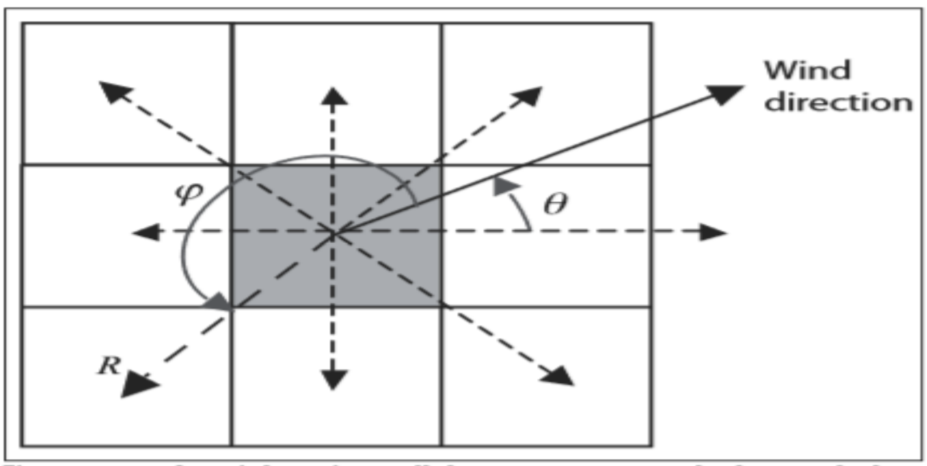

Figure 7. **An eight-point cellular automata method to calculate directional rate of spread.** φ = angle from the wind direction vector to the vector from the burning cell to an adjacent cell, R = rate of spread in the southwest direction, θ = angle of the wind direction vector. The dashed arrows represent the eight spread directions. The difference between the modeled and actual spread direction can be up to 22.5°, 11.25°, or 5.6° for models with 8-, 16-, and 32-point symmetric adjacency templates, respectively.

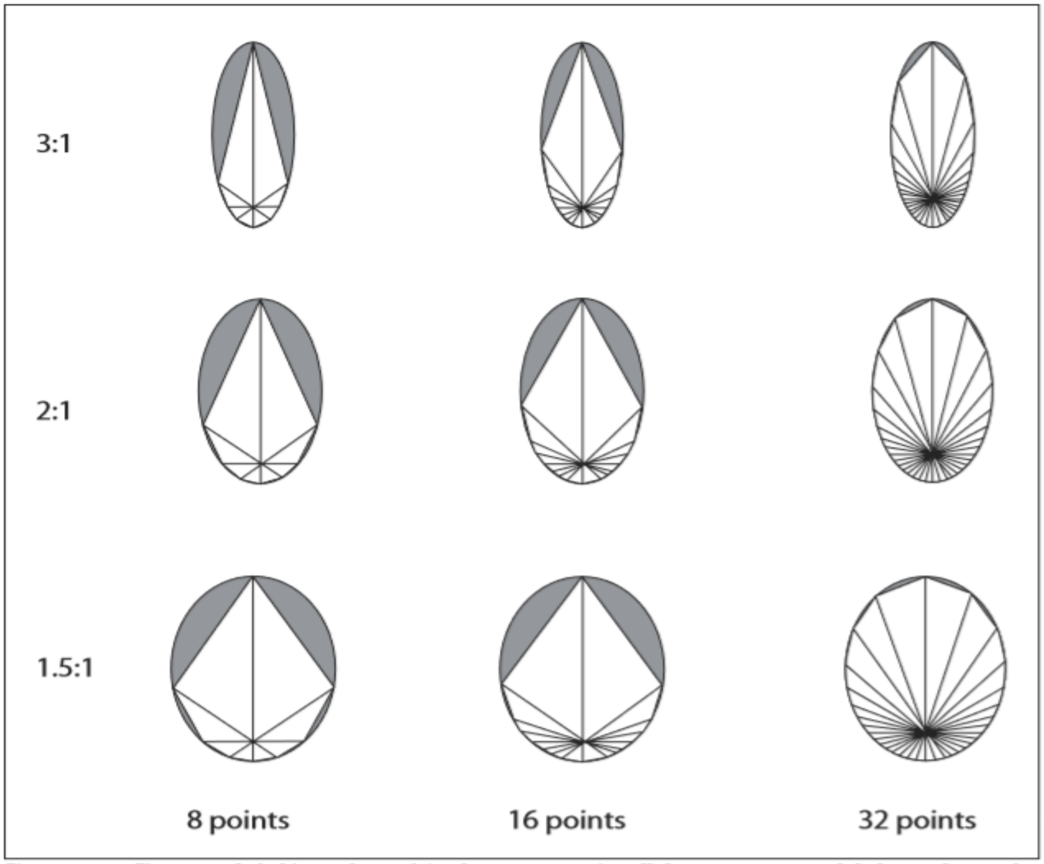

Figure 6. Fire growth (white polygons) in three symmetric cellular automata models layered over the simple elliptical fire growth model, according to length-to-breadth ratio (shown at left). The gray shaded areas within the ellipses represent the error or underestimation of fire growth.

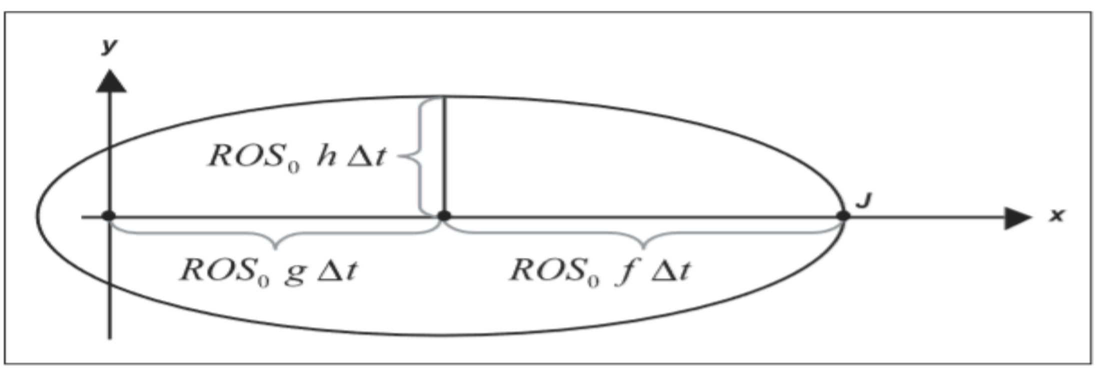

Figure 11. Propagation of an elliptical fire from an ignition point with a uniform wind speed in the x direction ($\theta = 0$), as described by Anderson et al. (1982). x and y = local point coordinates; ROS_0 = rate of spread (m/min) with no wind; f, g, h = wind-dependent parameters that change the rate of spread to account for the influence of wind; J = point where the spread direction vector intersects the ellipse when $\theta = 0$; Δt = time duration.

More information on the GDAL and OGR libraries can be found at www.gdal.org

Appendix C. ASCII Raster File Data

Source: www.firegrowthmodel.ca

The basic input format for the raster layers in Prometheus, such as FBP fuel types and elevation, is the ASCII raster file that the Environmental Systems Research Institute (ESRI) uses to represent raster data. ESRI is the author of GIS software including ArcGIS Desktop. The ASCII raster file is also known as an ArcInfo ASCII Grid, or AAIGrid for short. The ASCII raster file format is a standard format used to transfer raster data between various applications and provides an efficient means of working at the cell based level. The file contains a few lines of header data followed by lists of cell values.

The header includes the following information:

- ncols - number of columns in the data set.
- nrows - number of rows in the data set.
- xllcenter or xllcorner - x-coordinate of the center or lower-left corner of the lower-left cell.
- yllcenter or yllcorner - y-coordinate of the center or lower-left corner of the lower-left cell.
- cellsize - cell size (m) for the data set.
- NODATA_value - value in the file assigned to cells whose value is unknown.

The NODATA_value defaults to -9999. This value is used for NODATA cell values in all other matrix output files.

After the header, the data values are given cell-by-cell for the raster with the values starting at the upper left corner of the raster, moving from left to right. Cell values are delimited by spaces. No carriage returns are required at the end of each row in the data set. The number of columns in the header is used to determine when a new row begins. The number of cell values must be equal to the number of rows multiplied by the number of columns.

The input ASCII raster files required to run the Prometheus model must be created from ESRI supported raster data. All model output raster files will also be created as ASCII raster files. Thus all output files can be directly used and imported into GIS applications, such as ESRI's ArcGIS Desktop.

The following is an example of an ASCII raster file for the Nechako Lakes Electoral District.

Example portion of the ASCII raster file for the Southside.

landusegrid - Notepad

File Edit Format View Help

```
ncols         970
nrows         419
xllcorner     967003.0077
yllcorner     964384.3055
cellsize      100
NODATA_value  -9999
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Appendix D. Projection File

Source: www.firegrowthmodel.ca

Prometheus requires a projection file to import raster and vector data into a project. Raster files with FBP fuel types, elevation, and fuel or weather modifications can be used for input using any projection as long as they all use the same projection. The Prometheus application allows users to input vector data in many different projections, including the following:

- Albers Conic Equal-Area (Albers)
- Universal Transverse Mercator (UTM)
- 10 Degree Transverse Mercator (10 TM)
- Lambert Conformal Conic (Lambert)
- New Zealand Map Grid

Prometheus uses the PROJ4 cartographic projections library. This library, originally written by Gerald Evenden of the USGS, supports an extended suite of projections. The most commonly used projections are included in this application.

Vector data will be re-projected "on the fly" to the projection used by the Prometheus project (i.e., the projection of your FBP Fuel Type raster). Ignition points, lines and polygons can also be input interactively as X and Y geographic coordinates when New Ignition is selected in the Component View. Note that the ignition location in the Component View is always displayed in Relative Distance. Relative Distances assume the X and Y coordinates for the lower-left corner of your raster data are equal to 0, 0.

For the purpose of the research conducted as part of this thesis, the Albers Conic Equal-Area (Albers) projection was used.

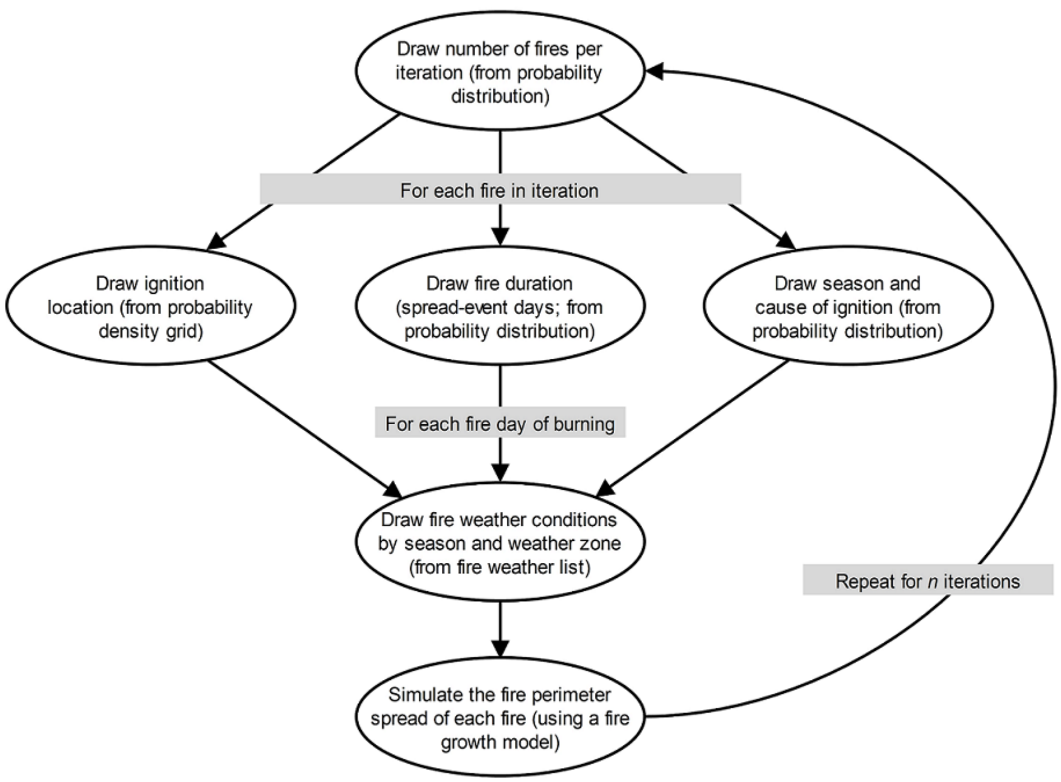
Appendix E. Burn-P3 model design and process

Source: www.firegrowthmodel.ca

The process overview of the Burn-P3 model is shown in the following figure. The boxes represent specific model processes and the inputs (i.e., state variables and modeling parameters) from which the information is drawn (in parentheses). The product resulting from these events is the area burned by the simulated fire(s) in one iteration. Burn probability is obtained by simulating a very large number of iterations and, ultimately, calculating how many times each pixel burned relative to the total number of iterations.

During a given iteration, the number of fires is determined either from a probability density function or a constant value. Then, for each fire, the ignition location, the season, the cause, and the duration of burning are determined from their respective state variables. For each new iteration, a new draw of the number of fires is made and the state variables are updated.

Daily fire weather conditions for each fire are then drawn and attached to each spread-event day. Unlike the previously described processes, for which a single value is drawn for a given fire, the process of adding fire weather to a fire occurs at a daily time step (fires can burn for more than one day).



Once the information pertaining to the ignition location, season, cause, duration of burning, and daily fire weather conditions is determined, fire spread is carried out using the fire growth sub-model Prometheus for all fires of a given iteration. The areas burned by each simulated fire in an iteration are recorded on the rasterized landscape. The burned areas from each iteration are compiled into a of burned areas where BP is calculated as follows:

$$BP_i = \frac{B_i}{N}$$

where B_i is the number of iterations in which pixel i experienced a fire and N is the number of iterations simulated.

This process is repeated for a pre-determined number of iterations.

Design concepts
Basic principles

The Burn-P3 model estimates the BP of the current landscape; therefore, it does not account for vegetation succession from one year to the next. Rather, Burn-P3 is based on the idea that capturing most of the natural variability in the processes driving fire ignition and spread generates more realistic fire patterns (Lertzman et al, 1998).

Although the variables driving fire growth are probabilistic (ignition location, duration of burning, daily fire weather), Burn-P3 also takes advantage of the fact that deterministic fire growth algorithms produce robust fire perimeter estimates (Finney 1999).

Modeling individual fires on a daily basis is computationally intensive. As such, we only model fires larger than a predetermined size (e.g., 200 ha). This is a sensible shortcut in most fire regimes. In the boreal forest of Canada, for example, fires of 200 hectares and larger account for ~97% of the area burned (Stocks et al. 2002).

Similarly, even though fires in the study area may burn for several weeks, significant fire growth is usually confined to a few days of high to extreme burning potential, termed spread-event days (Podur and Wotton 2011). In Burn-P3, only the spread-event days and their associated weather conditions were modeled. Like the minimum fire size, the use of spread-event days is a common shortcut in burn probability modeling (Finney 2005).

Emergence

Emergence arises when the interaction of inputs produces complex patterns that may be difficult or impossible to interpret (i.e., relate to any specific state variable). The resulting BP patterns can have a high degree of emergence. Parisien et al. (2010) documented that complex and unanticipated BP patterns can emerge in Burn-P3 from highly simplistic artificial inputs.

Prediction

At each pixel, the likelihood of being burned (i.e., BP) in one year is computed. Collectively, the pixels represent a grid or map of burn probabilities of the study area. Although the model is parameterized using real data, it is preferable to interpret these probabilities as relative to one another. That is, a pixel with a value of 0.3 is three times as likely to experience a fire as a pixel with a value of 0.1.

Interaction

In the study areas, two (or more) fires burning during a given year may merge. Clearly, a given pixel cannot be burned twice in a single year. This interaction is modeled in Burn-P3 as follows: within a given iteration, pixels that have been burned by a previous fire are not allowed to re-burn.

Stochasticity

To capture inter-annual variability, the number of fires to be simulated in each iteration is drawn from a probability density function. For example, two fires may be simulated across the landscape during the first iteration, whereas 20 fires may be simulated during the following iteration. It is also possible to specify a constant number of fires per iteration.

Because some combinations of season and cause experience more fires than others, fires simulated in Burn-P3 are probabilistically apportioned by season and cause, if these are specified. This stratification allowed the model to account for differences in fire weather patterns among seasons and causes, as well as the state of the vegetation (pre- vs. post-leaf flush and grass curing) that can affect fire spread.

After the number of fires has been determined for the iteration and the season of fire was chosen, the next step consists of selecting its ignition location. The ignition location of each fire is drawn from a probability density grid. Spatial patterns of ignitions may vary by season and cause. If a given fire ignition does not achieve the minimum size threshold (e.g., 200 ha), then another ignition is drawn until the total number of fires selected for the iteration are simulated.

The duration of burning is usually highly variable among wildfires. This variability is modeling in Burn-P3 by drawing the duration of burning of each fire from a frequency distribution of spread-event days. It is also possible to use a constant number of spread-event days per fire.

Daily fire weather conditions are then attached to each spread-event day in a partly random process that is described in the figure below. Fire weather is drawn from a list of historical fire-conducive weather conditions that is stratified by season and by weather zone, if these variables are specified. The daily fire weather conditions of this "fire weather list" are ordered by date; however, they only contain days for which the fire danger is conducive to fire spread. For each simulated fire, the fire weather conditions of the first spread-event day is randomly selected for the appropriate season and weather zone, and weather conditions of subsequent days were selected sequentially from the fire weather database for each additional spread-event day, thereby retaining the observed temporal variability in burning conditions. Alternatively, weather conditions can be selected randomly from a given combination of season and weather zone.

Step 1: Once the ignition location and season of a fire are determined, one day (i.e., one row) of fire weather conditions is randomly selected for the first spread-event day (SE1). In this example, the fire will be simulated in season S1 and located in Weather zone W3. The fire weather components (highlighted in grey) are retrieved.

Step 2: After fire weather for the first spread-event day is selected, subsequent daily fire weather is sequentially selected from the list. It this example, the fire will burn for 4 spread-event days SE1 to SE4.

Step 3: The daily fire weather conditions selected in Steps 1 and 2 are replicated according to the number of hours of burning per day. In this example, fires are simulated for 5 hours per day. The hourly fire weather conditions, which vary daily, are used to drive fire spread in Burn-P3.

Observation

Other than a BP map, Burn-P3 produces a table describing the size of each simulated fire, as well the ignition location, season, number of spread-event days, and the area burned in each fuel type. For calibration purposes, simulated fires sizes can be compiled into a frequency distribution that is compared to the observed fire size distribution derived from a fire atlas of the study area. Modifying the Burn-P3 state variables may affect both the mean of the distribution (i.e., mean fire size) and the shape of the distribution (i.e., how skewed it is). All state variables, as well as some of the Burn-P3 settings, notably the number of hours of burning per day, can affect simulated fire sizes. Calibration is performed heuristically by carefully adjusting the model inputs.

Burn-P3 can also produce a set of optional inputs in tabular or gridded format. One of these inputs consists of the record of iterations in which fires have burned for each pixel (Specialized outputs; Burn iterations). This input would allow the user to explore the distribution of fire intervals modeled in their Burn-P3 run. Another set of inputs, which can be in gridded or tabular (i.e., "raw") format, are derived from the FBP System primary outputs. These inputs are produced by recording an FBP System output of interest (e.g., fire intensity) at each pixel every time it is burned. From this information, selected summary statistics (i.e., mean, maximum, minimum, or median) or user-specified percentile values are computed and gridded to produce FBP System outputs.

Initialization

The state at the beginning of each iteration is the intact study landscape (i.e., without any simulated burnt areas). In other words, each iteration starts with a "clean slate", whereby the area burned by the previously simulated fires is removed from the landscape. Iterations are computed independently of one another.

Burn-P3 uses a number of predetermined constant settings. The number of daily hours of burning represents the number of hours of the day for which appreciable burning occurs, which is typically late morning to early evening. The minimum fire size sets a threshold on the simulated fire size so that very small fires are not simulated. The final setting is the length of the simulation (in iterations). The number of iterations must be high enough to yield a stable estimate of BP.

Some settings related to the season state variable were also constant across each simulation run. First, the leaves for the deciduous and mixed wood fuel types are usually off in the spring and on in the summer and fall seasons. Second, the percent curing of the grass fuel type also usually varies by season, whereby most of the aboveground biomass is either cured or dead in the spring.

Input data

Input data for Burn-P3 is usually based on observed historical databases.

In each iteration, the number of fires is usually sampled from a probability density function, whereby the values may decrease from the lowest (zero) to a large number of fires. The season of burning is drawn from a categorical probability density function. These distributions can be obtained from a data set such as the Canadian National Fire Database (http://cwfis.cfs.nrcan.gc.ca/en_CA/nfdb/poly), which represents an atlas of mapped fire perimeters.

The fire duration is drawn from a frequency distribution of spread-event days with values usually decreasing across its range (e.g., 1 to 12 days). This distribution can be obtained from a data set of daily fire progressions derived from MODIS fire detection data (http://activefiremaps.fs.fed.us/activefiremaps.php).

The daily fire weather conditions usually consist of real observations from weather stations. These can be extracted from a database of weather stations in and around the study landscape. Usually, only days corresponding to high and extreme fire weather danger are used. Weather stations that are unrepresentative of the surroundings (e.g., those on top of the highest mountain ridge) are usually not used for Burn-P3 modeling.

Sub models

The Prometheus fire growth model

Fire spread in Burn-P3 is based on the Prometheus fire growth model which was designed to calculate the spread of fire through complex terrain and fuels according to the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Tymstra et al. 2010). The spread mechanism of Prometheus belongs to a family of modern fire-growth algorithms that produce realistic burn patterns, including unburned islands. Unlike the other Burn-P3 inputs used in this study, fire growth is a deterministic; therefore, a given set of inputs will always result in the same fire perimeter. However, obtaining two identical fires is highly unlikely because of the modeled variability in the ignition location (hence the fuels that burn), season of burning (affecting the phonological state of the vegetation), and weather (including duration of burning and the daily fire weather conditions).

The Prometheus fire growth model can be downloaded from www.firegrowthmodel.ca

Appendix F. Pandora Input File requirements

Source: www.firegrowthmodel.ca

A space- or tab-delimited text file is used to set the parameters for each simulation in the batch job. The format is explained in the table below and displayed in the sample file. The parameters file can specify any number of simulations. Each simulation is defined by a set of parameters and values.

- The parameter names must be spelled exactly as listed below (case insensitive).
- Lines beginning with any other words are ignored.
- The first parameter for each simulation must be "Fire_Name".
- The rest of the parameters can be in any order, with this exception.
- Parameters identified as "optional" do not have to appear in the file.
- Parameters identified as "multiple" can appear in the file more than once.

Parameter	Content	Format
Fire_Name	User-selected name for this simulation	String
Projection_File	Location of projection file (.prj) Note:	File name including drive and path
FBP_GridFile	Location of fuel type gridascii file	File name including drive and path
Elev_GridFile	Location of elevation gridascii file (optional)	File name including drive and path; or "none"
WxStation_Lat	Latitude of weather station	Floating point number
WxStation_Lon	Longitude of weather station	Floating point number
WxStation_Elev	Elevation of weather station	Floating point number
Wx_File	Location of Prometheus-format weather data text file (multiple)	File name including drive and path
Init_FFMC	FFMC on first day of wx stream at hour specified by Init_Hour	Floating point number
Init_DMC	DMC on first day of weather stream	Floating point number
Init_DC	DC on first day of weather stream	Floating point number
Init_Hour	Hour associated with initial FFMC value (optional; default = 16)	Integer (hours since midnight)
FFMC_Method	Hourly FFMC calculation method (optional; default = 0) Note:	0 = Van Wagner 1 = Hybrid 2 = Lawson 5 = As specified in weather file

Grass_Curing	Grass curing in percent, and optional fuel grid value(s) for grass (optional; default = 75) Note:	Integer(s)
Start_DateTime	Simulation start date/time (optional; default is first ignition time)	dd/mm/yyyy:hh:mm:ss
Ign_DateTime	Ignition start date/time (optional if specified using Ign_Point or Ign_File)	dd/mm/yyyy:hh:mm:ss
Ign_X	X-coordinate of ignition location measured in grid cells from the left (west) of grid extent (optional)	Floating point number
Ign_Y	Y-coordinate of ignition location measured in grid cells from bottom (south) of analysis extent (optional)	Floating point number
Ign_Point	Date, time and location of ignition point (multiple; optional if ignition specified elsewhere)	Date (dd/mm/yyyy:hh:mm:ss), X (floating point number), Y (floating point number)
Ign_File	Date, time, and Shapefile (multiple, optional if ignition specified elsewhere)	dd/mm/yyyy:hh:mm:ss and file name including drive and path
Fuel_Table	Location of fuel lookup table (optional)	File name including drive and path; or "none"
Fuel_Patch	Fuel patch specifications (source fuel type, destination fuel type, Shapefile location) (optional, multiple)	2 integers and 1 file name with drive and path; separated by spaces or tabs; leave file name blank for landscape patch
Distance_Res	Distance threshold (maximum spread distance in one time step) (optional; default = 1)	Floating point number (distance in cells)
Perimeter_Res	Perimeter resolution (maximum distance between vertices) (optional; default = 1)	Floating point number (distance in cells)
Time_Zone	Time zone in hours from Greenwich (optional; default = -7)	Floating point number
Daylight_Saving	Flag for daylight saving time (optional; default = 0)	1 = yes; 0 = no DST

Burn_Period	Burn period settings (start hour, stop hour, min WS, max RH, min FWI) (optional)	5 integers separated by spaces or tabs; or "none"
Acceleration	Optional, default = 1	1 = yes; 0 = no
Buildup_Effect	Optional, default = 1	1 = yes; 0 = no
Terrain_Effect	Optional, default = 1	1 = yes; 0 = no
Greenup	Optional, default = 1	1 = yes; 0 = no
Duration	Length of simulation in hours (optional; default = 24)	Integer
Export_Every	Export perimeter to Shapefile every this many hours (optional; default=0) Note:	Integer; 0 = none Note:
Out_ShapeFiles	File name pattern for output perimeter Shapefiles (optional) Note:	File name including drive and path
Out_GridFiles	File name pattern for output FBP grid ascii files (optional) More information	File name including drive and path
Out_Components	Output FBP grid(s) to be exported (optional)	Key word(s)

Step 1: Specify the parameters file by clicking on **Browse** or typing in the file name.

Step 2: Select options.

There are two options available. When **Generate log file** is selected, a text file is produced recording Pandora's progress. This is primarily used for debugging, but can also be used to capture the area burned after each hour.

When **Ignore errors** is selected, any error messages will not be displayed in popup boxes. They will still be logged if the log file option is selected. The purpose of this option is to allow for processing to continue when errors occur. Needless to say, processing will only continue if the errors aren't too serious.

Step 3: Press the **Start** button

Simulation progress will be displayed during processing. The name and number of each simulation will appear in the text boxes as the batch job is processed.

Command line options:

Interaction with the dialog box can be avoided by specifying the parameters file name as an argument, for example:

```
pandora c:\data\parameters.txt
```

This will also cause Pandora to start processing the specified file immediately, and to shut down automatically when processing is finished.

To prevent the window from being displayed, use /nowin in the command line:

```
pandora /nowin c:\data\parameters.txt
```

The other options can also be specified as command line arguments, for example:

```
pandora /log /silent c:\data\parameters.txt
```

Sample Input File

The following sample input file runs two simulations.

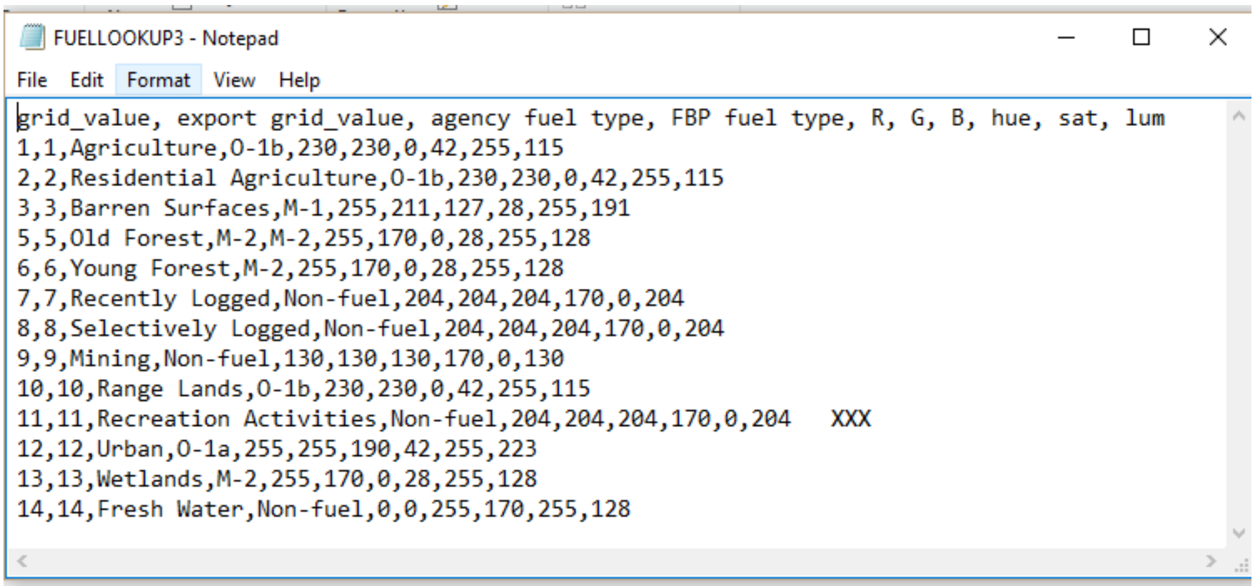
The first simulation does not specify an elevation grid, uses defaults for the fuel lookup table (and almost everything else), and requests one fire perimeter (the final fire perimeter) and no output grids.

The second simulation uses elevation; specifies a custom fuel lookup table file; specifies a distance threshold; switches off the buildup effect; restricts burning to between 5:00 AM and 10:00 PM; and requests 8 fire perimeters (one for each hour of growth) and two output grids (burned area and rate of spread).

```
Fire_Name  Dogbone
Projection_File  c:\pandora\dogbone\Landscape\Projection.prj
FBP_GridFile  c:\pandora\dogbone\Landscape\FBP25.asc
WxStation_Lat  52.1
WxStation_Lon  -115.2
WxStation_Elev  501.3
Wx_File  c:\pandora\dogbone\Weather1.txt
Init_FFMC  84.6
Init_DMC  50.5
Init_DC  397.6
Ign_DateTime  07/10/2001:11:00:00
Ign_X  25.38
```

Ign_Y 26.2
Duration 8
Export_Every 8
Out_ShapeFiles c:\pandora\dogbone\Output\DB_OutPerim
---------------Second fire starts here----------------
(Feel free to insert as many comments as you like, as long as they don't start with a key word).
Fire_Name Catrib
Projection_File c:\pandora\catrib\Landscape\Projection.prj
FBP_GridFile c:\pandora\catrib\Landscape\FBP25.asc
Elev_GridFile c:\pandora\catrib\Landscape\dem25.asc
WxStation_Lat 52.1
WxStation_Lon -115.2
WxStation_Elev 501.3
Wx_File c:\pandora\catrib\Weather1.txt
Init_FFMC 84.6
Init_DMC 50.5
Init_DC 397.6
Init_hour 12
FFMC_Method 0
Grass_curing 90 12 45
Ign_Point 07/10/2001:11:00:00 25.38 26.2
Ign_File 07/10/2001:12:30:00 c:\pandora\catrib\ign2.shp
Fuel_Table c:\pandora\catrib\fuels.lut
Distance_Res 1.5
Buildup_Effect 0
Daylight_Saving 1
Burn_Period 5 22 0 100
Duration 8
Export_Every 1
Out_ShapeFiles c:\pandora\catrib\Output\CR_OutPerim
Out_GridFiles c:\pandora\catrib\Output\CR_OutGrid
Out_Components burn ros

Example of a fuel lookup table:



FUELLOOKUP3 - Notepad

File Edit Format View Help

```
grid_value, export grid_value, agency fuel type, FBP fuel type, R, G, B, hue, sat, lum
1,1,Agriculture,O-1b,230,230,0,42,255,115
2,2,Residential Agriculture,O-1b,230,230,0,42,255,115
3,3,Barren Surfaces,M-1,255,211,127,28,255,191
5,5,Old Forest,M-2,M-2,255,170,0,28,255,128
6,6,Young Forest,M-2,255,170,0,28,255,128
7,7,Recently Logged,Non-fuel,204,204,204,170,0,204
8,8,Selectively Logged,Non-fuel,204,204,204,170,0,204
9,9,Mining,Non-fuel,130,130,130,170,0,130
10,10,Range Lands,O-1b,230,230,0,42,255,115
11,11,Recreation Activities,Non-fuel,204,204,204,170,0,204   XXX
12,12,Urban,O-1a,255,255,190,42,255,223
13,13,Wetlands,M-2,255,170,0,28,255,128
14,14,Fresh Water,Non-fuel,0,0,255,170,255,128
```

Appendix G. Discrete Probability Density Function: Poisson

Source: www.mathwave.com

This Appendix describes the general application of the Poisson distribution function.

The Poisson distribution function, named after French mathematician Siméon Denis Poisson, is a discrete probability function used extensively to express the probability of a given number of events occurring in fixed interval of time, space, distance, area or volume. An important condition for the application of this function is that its events have a memoryless property. In other words, every event occurs independently of the time of the preceding event.

An event can occur 0, 1, 2, … times in an interval. The average number of events in an interval is designated λ(lambda). Lambda is the event rate, also called the rate parameter. The probability of observing k events in an interval is given by the probability density function:

$$P(k \text{ events in interval}) = \frac{\lambda^k e^{-\lambda}}{k!}$$

The following parameters and equations apply for this function:

Poisson Distribution

Parameters

λ - continuous event rate ($\lambda > 0$)

Domain

$0 \leq x < +\infty$ (discrete)

Probability Density Function

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

Cumulative Distribution Function

$$F(x) = e^{-\lambda} \sum_{i=0}^{x} \frac{\lambda^i}{i!}$$

Mathwave Easyfit was used to determine the best fit to existing data on wildfire count. The Poisson distribution function yielded the best overall fit in each of the six months analyzed, except for July, which resulted in the D. Uniform as best-fitting function. However, overall when considering all six months, the Poisson density function gave the best results and was therefore used for random number generations.

April

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	Geometric	0.92647	2	106.39	2
2	Poisson	0.9237	1	104.39	1
3	Bernoulli	No fit (data max > 1)			
4	Binomial	No fit			
5	D. Uniform	No fit			
6	Hypergeometric	No fit			
7	Logarithmic	No fit (data min < 1)			
8	Neg. Binomial	No fit			

Poisson

λ 0.07937

May

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	D. Uniform	0.5	1	30.084	3
2	Geometric	0.67742	3	29.468	2
3	Poisson	0.62115	2	24.49	1
4	Bernoulli	No fit (data max > 1)			
5	Binomial	No fit			
6	Hypergeometric	No fit			
7	Logarithmic	No fit (data min < 1)			
8	Neg. Binomial	No fit			

Poisson

λ 0.47619

June

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	D. Uniform	0.5	1	27.964	1
2	Geometric	0.75904	3	42.478	3
3	Poisson	0.728	2	37.669	2
4	Bernoulli	No fit (data max > 1)			
5	Binomial	No fit			
6	Hypergeometric	No fit			
7	Logarithmic	No fit (data min < 1)			
8	Neg. Binomial	No fit			

Poisson

λ 0.31746

July

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	D. Uniform	0.42857	1	28.931	3
2	Geometric	0.5431	3	16.482	2
3	Poisson	0.43116	2	13.742	1
4	Bernoulli	No fit (data max > 1)			
5	Binomial	No fit			
6	Hypergeometric	No fit			
7	Logarithmic	No fit (data min < 1)			
8	Neg. Binomial	No fit			

Poisson

λ 0.84127

August

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	D. Uniform	0.5	1	33.128	3
2	Geometric	0.63	3	23.963	2
3	Poisson	0.55583	2	19.302	1
4	Bernoulli	No fit (data max > 1)			
5	Binomial	No fit			
6	Hypergeometric	No fit			
7	Logarithmic	No fit (data min < 1)			
8	Neg. Binomial	No fit			

Poisson

λ 0.5873

September

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling	
		Statistic	Rank	Statistic	Rank
1	D. Uniform	0.66667	1	48.066	2
2	Geometric	0.79747	3	51.177	3
3	Poisson	0.77572	2	46.933	1
4	Bernoulli	No fit (data max > 1)			
5	Binomial	No fit			
6	Hypergeometric	No fit			
7	Logarithmic	No fit (data min < 1)			
8	Neg. Binomial	No fit			

Poisson

λ 0.25397

Appendix H. General Extreme Event Distributions

Sources: www.mathwave.com and Williardson, 2011

This Appendix describes the general application of the extreme event distributions and the determination logic for finding the best fit to data related to wildfire size.

Several probability density function families exist for extreme event evaluations of natural phenomena. The following groups can be made (Williardson, 2011):

- Normal: Normal, Log-Normal (2), Log-Normal (3)
- Gamma: Exponential, Gamma (2), Pearson III, Log-Pearson III
- Extreme Value: Gen. Extreme Value, Extreme Value Type 1, Weibull
- Wakeby: Wakeby (5), Wakeby (4), Generalized Pareto
- Logistic: Logistic, Generalized Logistic

Each of these probability models has specific properties but they have in common that they all lend themselves to the evaluation of extreme event data. The distributions with many parameters are very sensitive to data set size. These distributions also have other limitations require careful consideration when selecting a distribution (Willardson, 2011).

Mathwave Easyfit was used to determine the best fit to existing data on wildfire size.
The results are given below, followed by a description of characteristics of each of the selected probability density functions chosen.

Goodness of Fit for Wildfires in the month of May

Human Cause

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Frechet	0.14202	4	0.58943	4	0.17973	4
2	Frechet (3P)	0.09392	1	0.18809	1	0.0448	3
3	Inv. Gaussian	0.20381	6	0.98372	6	1.9674	5
4	Inv. Gaussian (3P)	0.09679	2	0.20508	3	0.00944	1
5	Pearson 5	0.17017	5	0.67842	5	2.0552	6
6	Pearson 5 (3P)	0.0982	3	0.20458	2	0.03604	2

Lightning Cause

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Error	0.24199	1	0.69944	3	N/A	
2	Uniform	0.24205	2	0.69942	2	N/A	
3	Wakeby	0.25423	3	0.67308	1	N/A	

Rank 1

Human Cause

Frechet (3P) [#16]

Kolmogorov-Smirnov

Sample Size	23
Statistic	0.09392
P-Value	0.97562
Rank	3

α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.21645	0.24746	0.2749	0.30728	0.32954
Reject?	No	No	No	No	No

Anderson-Darling

Sample Size	23
Statistic	0.18809
Rank	1

α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No

Chi-Squared

Deg. of freedom	2
Statistic	0.0448
P-Value	0.97785
Rank	3

α	0.2	0.1	0.05	0.02	0.01
Critical Value	3.2189	4.6052	5.9915	7.824	9.2103
Reject?	No	No	No	No	No

Lightning Cause

Wakeby [#61]

Kolmogorov-Smirnov

Sample Size	7
Statistic	0.25423
P-Value	0.66875
Rank	3

α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.38148	0.43607	0.48342	0.53844	0.57581
Reject?	No	No	No	No	No

Anderson-Darling

Sample Size	7
Statistic	0.67308
Rank	3

α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No

Rank 2

Human Cause

Inv. Gaussian (3P) [#28]

Kolmogorov-Smirnov

Sample Size	23
Statistic	0.09679
P-Value	0.96804
Rank	4

α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.21645	0.24746	0.2749	0.30728	0.32954
Reject?	No	No	No	No	No

Anderson-Darling

Sample Size	23
Statistic	0.20508
Rank	3

α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No

Chi-Squared

Deg. of freedom	2
Statistic	0.00944
P-Value	0.99529
Rank	1

α	0.2	0.1	0.05	0.02	0.01
Critical Value	3.2189	4.6052	5.9915	7.824	9.2103
Reject?	No	No	No	No	No

Lightning Cause

Uniform [#60]

Kolmogorov-Smirnov

Sample Size	7
Statistic	0.24205
P-Value	0.72541
Rank	2

α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.38148	0.43607	0.48342	0.53844	0.57581
Reject?	No	No	No	No	No

Anderson-Darling

Sample Size	7
Statistic	0.69942
Rank	5

α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No

Rank 3

Human Cause

Pearson 5 (3P) [#45]

Kolmogorov-Smirnov

Sample Size	23
Statistic	0.0982
P-Value	0.96383
Rank	6

α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.21645	0.24746	0.2749	0.30728	0.32954
Reject?	No	No	No	No	No

Anderson-Darling

Sample Size	23
Statistic	0.20458
Rank	2

α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No

Chi-Squared

Deg. of freedom	2
Statistic	0.03604
P-Value	0.98214
Rank	2

α	0.2	0.1	0.05	0.02	0.01
Critical Value	3.2189	4.6052	5.9915	7.824	9.2103
Reject?	No	No	No	No	No

Lightning Cause

Error [#11]

Kolmogorov-Smirnov

Sample Size	7
Statistic	0.24199
P-Value	0.7257
Rank	1

α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.38148	0.43607	0.48342	0.53844	0.57581
Reject?	No	No	No	No	No

Anderson-Darling

Sample Size	7
Statistic	0.69944
Rank	6

α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No

Wakeby Distribution

The following parameters are used:
α, β, γ, δ, ξ (all continuous)

The following conditions are imposed:
$\alpha \neq 0$ or $\gamma \neq 0$,
$\beta + \delta > 0$ or $\beta = \gamma = \delta = 0$,
if $\alpha = 0$, then $\beta = 0$,
if $\gamma = 0$, then $\delta = 0$,
$\gamma \geq 0$ and $\alpha + \gamma \geq 0$.

Domain

$\xi \leq x < \infty$ if $\delta \geq 0$ and $\gamma > 0$,
$\xi \leq x \leq \xi + \alpha/\beta - \gamma/\delta$ if $\delta < 0$ or $\gamma = 0$.

Quantile Function (Inverse Cumulative Distribution Function)

The Wakeby distribution is defined by the quantile function (Inverse CDF):

$$x(F) = \xi + \frac{\alpha}{\beta}\left(1 - (1-F)^{\beta}\right) - \frac{\gamma}{\delta}\left(1 - (1-F)^{-\delta}\right)$$

Fatigue Life (Birnbaum-Saunders) Distribution

Parameters

α - continuous shape parameter ($\alpha > 0$)
β - continuous scale parameter ($\beta > 0$)
γ - continuous location parameter ($\gamma \equiv 0$ yields the two-parameter Fatigue Life distribution)

Domain

$\gamma < x < +\infty$

Three-Parameter Fatigue Life Distribution

Probability Density Function

$$f(x) = \frac{\sqrt{(x-\gamma)/\beta} + \sqrt{\beta/(x-\gamma)}}{2\,\alpha\,(x-\gamma)} \cdot \phi\left(\frac{1}{\alpha}\left(\sqrt{\frac{x-\gamma}{\beta}} - \sqrt{\frac{\beta}{x-\gamma}}\right)\right)$$

Cumulative Distribution Function

$$F(x) = \Phi\left(\frac{1}{\alpha}\left(\sqrt{\frac{x-\gamma}{\beta}} - \sqrt{\frac{\beta}{x-\gamma}}\right)\right)$$

Two-Parameter Fatigue Life Distribution

Probability Density Function

$$f(x) = \frac{\sqrt{x/\beta} + \sqrt{\beta/x}}{2\,\alpha\,x} \cdot \phi\left(\frac{1}{\alpha}\left(\sqrt{\frac{x}{\beta}} - \sqrt{\frac{\beta}{x}}\right)\right)$$

Cumulative Distribution Function

$$F(x) = \Phi\left(\frac{1}{\alpha}\left(\sqrt{\frac{x}{\beta}} - \sqrt{\frac{\beta}{x}}\right)\right)$$

where ϕ is the PDF of the standard Normal distribution, and Φ is the Laplace Integral.

Log-Pearson 3 Distribution

Parameters

α - continuous parameter ($\alpha > 0$)
β - continuous parameter ($\beta \neq 0$)
γ - continuous parameter

Domain

$$0 < x \leq e^{\gamma} \qquad \beta < 0$$
$$e^{\gamma} \leq x < +\infty \qquad \beta > 0$$

Probability Density Function

$$f(x) = \frac{1}{\mathrm{x}\,|\beta|\,\Gamma(\alpha)} \left(\frac{\ln(\mathrm{x}) - \gamma}{\beta} \right)^{\alpha-1} \exp\left(-\frac{\ln(\mathrm{x}) - \gamma}{\beta} \right)$$

Cumulative Distribution Function

$$F(x) = \frac{\Gamma_{(\ln(x)-\gamma)/\beta}(\alpha)}{\Gamma(\alpha)}$$

Lognormal Distribution

Parameters

σ - continuous parameter ($\sigma > 0$)
μ - continuous parameter
γ - continuous location parameter ($\gamma \equiv 0$ yields the two-parameter Lognormal distribution)

Domain

$\gamma < x < +\infty$

Three-Parameter Lognormal Distribution

Probability Density Function

$$f(x) = \frac{\exp\left(-\frac{1}{2}\left(\frac{\ln(x-\gamma)-\mu}{\sigma}\right)^2\right)}{(x-\gamma)\,\sigma\sqrt{2\pi}}$$

Cumulative Distribution Function

$$F(x) = \Phi\left(\frac{\ln(x-\gamma)-\mu}{\sigma}\right)$$

Two-Parameter Lognormal Distribution

Probability Density Function

$$f(x) = \frac{\exp\left(-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2\right)}{x\,\sigma\sqrt{2\pi}}$$

Cumulative Distribution Function

$$F(x) = \Phi\left(\frac{\ln x-\mu}{\sigma}\right)$$

where Φ is the Laplace Integral.

Frechet Distribution

Parameters

α - continuous shape parameter ($\alpha > 0$)
β - continuous scale parameter ($\beta > 0$)
γ - continuous location parameter ($\gamma \equiv 0$ yields the two-parameter Frechet distribution)

Domain

$\gamma < x < +\infty$

Three-Parameter Frechet Distribution

Probability Density Function

$$f(x) = \frac{\alpha}{\beta}\left(\frac{\beta}{x-\gamma}\right)^{\alpha+1} \exp\left(-\left(\frac{\beta}{x-\gamma}\right)^{\alpha}\right)$$

Cumulative Distribution Function

$$F(x) = \exp\left(-\left(\frac{\beta}{x-\gamma}\right)^{\alpha}\right)$$

Two-Parameter Frechet Distribution

Probability Density Function

$$f(x) = \frac{\alpha}{\beta}\left(\frac{\beta}{x}\right)^{\alpha+1} \exp\left(-\left(\frac{\beta}{x}\right)^{\alpha}\right)$$

Cumulative Distribution Function

$$F(x) = \exp\left(-\left(\frac{\beta}{x}\right)^{\alpha}\right)$$

Pearson 5 (3P)

Parameters

α - continuous shape parameter ($\alpha > 0$)
β - continuous scale parameter ($\beta > 0$)
γ - continuous location parameter ($\gamma \equiv 0$ yields the two-parameter Pearson 5 distribution)

Domain

$\gamma < x < +\infty$

Three-Parameter Pearson 5 Distribution

Probability Density Function

$$f(x) = \frac{\exp(-\beta/(x-\gamma))}{\beta\,\Gamma(\alpha)\,((x-\gamma)/\beta)^{\alpha+1}}$$

Cumulative Distribution Function

$$F(x) = 1 - \frac{\Gamma_{\beta/(x-\gamma)}(\alpha)}{\Gamma(\alpha)}$$

Two-Parameter Pearson 5 Distribution

Probability Density Function

$$f(x) = \frac{\exp(-\beta/x)}{\beta\,\Gamma(\alpha)\,(x/\beta)^{\alpha+1}}$$

Cumulative Distribution Function

$$F(x) = 1 - \frac{\Gamma_{\beta/x}(\alpha)}{\Gamma(\alpha)}$$

Inverse Gaussian Distribution

Parameters

λ - continuous parameter ($\lambda > 0$)
μ - continuous parameter ($\mu > 0$)
γ - continuous location parameter ($\gamma \equiv 0$ yields the two-parameter Inverse Gaussian distribution)

Domain

$$\gamma < x < +\infty$$

Three-Parameter Inverse Gaussian Distribution

Probability Density Function

$$f(x) = \sqrt{\frac{\lambda}{2\pi (x-\gamma)^3}} \exp\left(-\frac{\lambda (x-\gamma-\mu)^2}{2\mu^2 (x-\gamma)}\right)$$

Cumulative Distribution Function

$$F(x) = \Phi\left(\sqrt{\frac{\lambda}{x-\gamma}}\left(\frac{x-\gamma}{\mu} - 1\right)\right) + $$
$$+\Phi\left(-\sqrt{\frac{\lambda}{x-\gamma}}\left(\frac{x-\gamma}{\mu} + 1\right)\right) \exp(2\lambda/\mu)$$

Two-Parameter Inverse Gaussian Distribution

Probability Density Function

$$f(x) = \sqrt{\frac{\lambda}{2\pi x^3}} \exp\left(-\frac{\lambda (x-\mu)^2}{2\mu^2 x}\right)$$

Cumulative Distribution Function

$$F(x) = \Phi\left(\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} - 1\right)\right) + \Phi\left(-\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} + 1\right)\right) \exp(2\lambda/\mu)$$

where Φ is the Laplace Integral.