Decreasing average wildfire size through random fuel treatments: A boreal forest case study.

by

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Abstract

Area burned in boreal forests is increasing due to climate change effects and regional increases in fuels due to a history of successful fire suppression. An increase in area burned threatens valuable resources and infrastructure in timber resources areas and communities. The ecological integrity of protected areas may also be threatened if fires increase in frequency and size beyond what would have occurred prior to effective fire suppression and the effects of climate change. Fuel management is one strategy being tested by fire management agencies and researchers to address these concerns. However the pattern of fuel management that best regulates area burned has yet to be determined. This thesis investigates random fragmentation of highly flammable fuels in the boreal forests of North-western Ontario. A case study of Quetico Provincial Park is used. Using the fire growth simulation model, Prometheus, I tested whether, under extreme fire behaviour conditions, fuel isolation (FI) and fuel conversion (FC) were effective at reducing average area burned in the park. Through the simulation of over 21,000 large fires, I determined that FI and FC are effective in significantly reducing area burned for this case study. Based on these findings, random FI and FC should be studied further on a regional basis and as a prescriptive, proactive method of reducing area burned in boreal forests.

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Chapter 1
Introduction

The combination of increased *fuel hazards*, due to a history of fire suppression, and *extreme weather events*, due to climate change effects, is resulting in larger, more destructive wildfires in the boreal biome (Agee, 1998; Conard, Hartzel, Hilbruner & Zimmerman, 2001; Gillett, Weaver, Zwiers & Flannigan, 2004; Gollberg, Neuenschwander & Ryan, 2001; Moore, Covington & Fule, 1999; Omi & Martinson, 2004). Extremely large wildfires could threaten lives, property and other resource values (Hirsch, Kafka & Todd, 2004; Omi, 2005). Due to a variety of conflicting resource management and land use pressures, economic interests and safety concerns, it is prudent to explore proactive fire management planning to reduce the potential of catastrophic wildfire events.

Though fire is a necessary natural process within many ecosystems, catastrophic wildfires with extreme fire behaviour pose a significant threat to many values and are difficult to suppress through traditional methods (Hirsch et al., 2004; Omi, 2005). Wildfires are any fires that are difficult to control and therefore burn across a landscape, consuming mainly vegetation in addition to infrastructure (Clarke, Brass & Riggan, 1994). Extremely large wildfires threaten a wide variety of values including timber resources, critical infrastructure (power grids, drinking water supplies), buildings, Species at Risk, wildlife habitat, soil productivity and other ecological processes. Firefighter and public health and safety are also at risk (Graham, McCaffrey & Jain, 2004; Loehle, 2004; Omi, 2005).

My research examines how random fuel treatments in highly flammable fuels affect average fire size under *extreme fire behaviour* conditions, using a boreal forest case study. It is important to recognize that the 'random' component of this study refers to a random selection of fuel polygons within targeted highly flammable fuels. The fuel treatments are not randomly selected from all fuel types across the landscape, and therefore are only random in the sense of being scattered across a landscape, and are not strategic bulkhead fuel break treatments. Fire occurrence and area burned has been increasing in the boreal biome due to extended and warmer fire seasons, frequent extreme weather events (Bergeron, Gauthier, Kafka, Lefort & Lesieur, 2001; Flannigan, Stocks & Wotton, 2000; McCoy & Burn, 2005; Weber & Flannigan, 1997; Westerling, Hildago, Cayan & Swetnam, 2006) and an accumulation of fuels (Suffling, 1992), therefore a reduction in area burned is desirable if we wish to restore a natural disturbance regime and protect *values at risk*. This research will assist in identifying a minimum threshold for the percentage of random fuel treatments needed to significantly reduce average wildfire size under extreme fire behaviour conditions. Therefore my hypothesis is that randomly isolating and converting highly flammable fuels in the boreal forest will decrease average area burned under extreme fire behaviour conditions.

Research objectives include simulating wildfires in Ontario boreal forests under extreme wildfire conditions, and testing the concept of using random fuel treatments to reduce wildfire size, which are on the rise due to fuel accumulation and climate change.

Three research questions addressed are:

1. Will randomly fragmenting (isolating) highly flammable boreal forest fuels decrease average wildfire size in Quetico Provincial Park?
2. Can fuel conversion (from coniferous to deciduous) decrease average wildfire size in North-western Ontario?
3. Are fragmentation and fuel conversion worth researching further as a prescriptive, proactive method to reduce the potential of catastrophic wildfires in boreal forests?

Large wildfires are a natural component of many forest communities. Political and economic fear has created the misconception that all large wildfires are ecologically catastrophic, when in fact it is the human losses that are catastrophic (Kauffman, 2004). However, planning and management practices, such as fire suppression, have resulted in wildfires occurring beyond their historical range of size and intensity (Kauffman, 2004). Making assumptions that all wildfires are unwanted can lead to further disruption of natural ecological functions. For example, the Healthy Forest Initiative (2002) and the Healthy Forest Restoration Act (2003) were created in the United States with the intent of reducing catastrophic wildfires by restoring healthy forests (Kauffman, 2004). This law is based on achieving healthy forests through thinning and other logging activities in an attempt to reduce all wildfires (Kauffman, 2004). Yet scientists agree that restoring natural processes, such as fire, is critical to maintaining forest structure and health. Fire management planning should be based on sound scientific research before wide-scale implementation.

Natural resource extraction is of significant importance to northern economies that rely on timber harvesting and spin-off industries. Forest fire frequency, intensity and area burned concern the forest industry, government agencies and local communities, as fires limit the availability for harvestable timber resources (Flannigan et al., 2000; Suffling, 1992; Weber & Flannigan, 1997). A study by Martell (1994) found that Ontario's forest fire management system was effective at reducing timber lost to fire in the majority of the districts under study. This was achieved through traditional fire suppression methods, the costs of which can be directly attributed to area burned each year. Yet this figure has been rising steadily, indicating an increased area burned (Weber & Flannigan, 1997). It is reasonable to expect increasing fire suppression measures, including proactive approaches, will be needed given the pressure of timber harvesting quotas in a shifting fire regime (Weber & Flannigan, 1997).

This research focuses on one of the main objectives of FireSmart forest management: the reduction of average area burned from unwanted wildfire. The word "unwanted" is a deliberate choice; it is a normative term and the implication is that fire suppression may be justified when values at risk are threatened but it does not mean that all large wildfires should be suppressed everywhere.

FireSmart principles are critical to the conceptual framework for this study, as there is potential to extrapolate concepts of fuel isolation and reduction outside of a community protection context. There is an important distinction between the known FireSmart community protection strategies and the FireSmart forest management conceptual theory I studied. Established FireSmart community protection approaches use *strategic* fuel isolation (fuel breaks) and fuel reduction to reduce wildfire risk surrounding an area with high values at risk. This research studies the reduction of fuel hazards applied *randomly* across the landscape in order to decrease the overall size of catastrophic wildfires, thus decreasing the potential of wildfires escaping suppression controls and threatening values at risk. This would allow fire to continue as a natural disturbance process without necessitating large-scale suppression efforts for a large proportion of fires close to the *wildland urban interface*, timber resources and other ecological values.

The effectiveness of FireSmart forest management landscape fuel treatments is still under debate. In this research I used fire growth modelling to run thousands of fires on a landscape of original fuels (the control) and subsequently on a series of treated landscapes. The treatments consisted of 16 landscapes with randomly fragmented highly flammable fuels. The average area burned from these fires was statistically analyzed to determine if the fragmentation of fuels resulted in a reduction in fire size in a boreal forest case study. It is a useful exercise to test fuel management planning concepts using realistic fuel and weather data, opposed to simulated landscapes. This research uses real world data and realistic input parameters in order to maintain relevance to the Canadian boreal forest.

As using field experiments to study the effects of fuel treatments under extreme fire behaviour conditions is difficult (Agee & Skinner, 2005), fire growth modelling can be used to predict and evaluate the impacts of fuel management strategies and plan for future management (Fernandes & Botelho, 2003). There was high-quality data available for Quetico Provincial Park, located in North-western Ontario. This is important in fire growth modelling because quality of input data considerably affects quality of modelling output. A case study was important to this research as it provided a realistic vegetation mosaic for testing conceptual fuel fragmentation theories.

This research does not provide a prescriptive method to reduce wildfire size, but rather a conceptual approach that may later be combined with stand and compartment level fuel management research to apply in the field. The concepts of fuel isolation and conversion are studied as a theoretical model for the basis of future prescriptive research. As this research focuses on the conceptual theory of using fragmentation to reduce area burned, the mechanical methods of achieving fuel isolation and conversion will not be explored.

Natural resource management planning is moving towards an integrated and co-ordinated approach to cross-boundary resource issues. Fire management is one issue that requires such cooperation between industry, government and private landowners. Effective resource management planning that protects values at risk is needed, while continuing to maintain the natural disturbance role of fire in the boreal biome.

Fire management planning must incorporate multiple spatial scales. Spatial scale can be defined as both the resolution or grain size of the data and the landscape extent or size (Boychuk & Perera, 1997). The context of the research defines the appropriate scale. My research examines the landscape-level phenomena of a subsection of boreal forest fires in Quetico Provincial Park and a buffer area, which is approximately 5542 km^2 in size. Though the conclusions from this study are specific to a region of North-western Ontario, the theory behind the application of random fuel fragmentation can be used as a planning component for fire management in other boreal regions.

In the context of the following literature, it is clear that a fire management issue is arising out of a history of successful fire suppression, coupled with the effects of climate change: average area burned is increasing in comparison to historical fire regimes. This equates to larger, more frequent catastrophic fire events that threaten the values inherent to protected areas, crown land and the wildland urban interface. Planning methods to mitigate this risk are needed. The risks associated with large wildfire events may potentially effect three areas: 1) Protected areas, 2) Timber resources, and 3) Interface communities. The concerns specific to each area are:

- Stand-replacing fires are part of the boreal forest fire regime and should be reintroduced in protected areas. However, large wildfires are difficult to suppress, may escape the park boundaries and threaten surrounding resource values and communities. Resource planners should determine a way to allow some wildfires to occur in a park in an effort to restore ecosystem integrity, but limit risks normally associated with extreme large wildfire events. This may be possible by reducing the average wildfire size through random fuel treatments.

- Timber resources are frequently threatened by extreme wildfire events. With an increase in these events, timber companies need new fire management strategies to protect their resources. By limiting average area burned by incorporating random fuel treatment patterns into their strategic planning, they may help to protect timber resources.

- Communities surrounded by boreal forests are at greater risk from extreme wildfire events as a result of climate change effects and potentially historic fire suppression activities. FireSmart community protection may not sufficiently protect these communities from extreme wildfire events; therefore new fuel management strategies should be researched.

To determine if average area burned can be reduced through randomly fragmenting highly flammable fuels, a case study of boreal forests typical to North-western Ontario was used. Fire growth simulation modelling is used as a tool in an attempt to answer this question. Specifically, a wave propagation model was used (vector modelling). The batch program Pandora was used to access the modelling engine of Prometheus, to simulate multiple iterations of fires on a control map and on 16 fuel treatments.

In a brief synopsis, I shall explore the rise of the fire suppression era, and how this has led to an accumulation of fuel hazards thus affecting boreal forest fire regimes. From there, I shall briefly review the concept of fuel management strategies used to mitigate risks associated with wildfires. After exploring the effects of climate change on fire regimes, we will examine fire simulation modelling, a relatively new planning and research tool for studying fire management strategies. Methods used for fire growth modelling and necessary data inputs will be outlined, followed by results of this research and a discussion of the importance of these findings.

Chapter 2
Literature Review

2.1 Fire Management in North America

Fire is an important large-scale disturbance in many ecosystems worldwide (Anderson et al., 1998; Morgan, Hardy, Swetnam, Rollins & Long, 2001). Fire management likely predates recorded history. In North America, aboriginals may have used fire management for hunting, berry production and warfare as far back as c 11,000 BCE (post the last major glaciation period) (Heinselman, 1996; Martinson & Omi, 2003; Pyne, 1982). This abruptly changed with the arrival of European settlers, which was generally characterized by an immediate increase of fire due to accidental ignitions, followed by a trend towards fire suppression by the early to mid 1900s for many regions in North America. In the 1980s, policy and fire management standards in North America shifted towards a combination of fire use, fire tolerance and fire control, in an attempt to balance economic, social and ecological considerations. The future of fire management will be determined by the interplay between political influence and scientific rigour.

2.1.1 Pre-suppression era in North America

Natural fire occurrence has always been an influential large-scale disturbance (Heinselman, 1996) in North America. Through the combination of oral history and fire history studies, researchers have determined that native peoples used fire for thousands of years on all continents, except Antarctica, (Omi, 2005). According to a meta-analysis by Martinson & Omi (2003) of North American fire history studies, native firings were a substantial component of the fire regime in North America. However, studies in Quetico Provincial Park are inconclusive as to whether native firings significantly influenced historic fire regimes (Suffling & Speller, 1998).

2.1.2 Fire Suppression Era in North America

North-western Ontario did not escape the fire suppression era, though the immediate impact of suppression would have been less catastrophic (in the sense of gradual ecosystem changes) because there was no mass prescribed burning by native peoples (Fritz, Suffling & Younger, 1993). Suppression usually reduces the number of low and moderate-intensity fires, thus fundamentally changing the landscape pyrodiversity (Graham et al., 2004; Stephens, 1998). Depending on the forest type and location, this can result in significant accumulations of biomass that inhibits ecosystem functioning (Conard et al., 2001; Gollberg et al., 2001; Pyne, 1982). The additional biomass provides large fuel beds thereby increasing the risk for extremely large, intense catastrophic wildfires that threaten lives, property and neighbouring lands (Agee, 1998; Conard et al., 2001; Gollberg et al., 2001; Moore et al., 1999; Omi & Martinson, 2004), especially in the context of longer, warmer fire seasons as a result of global climate change (Conard et al., 2001).

Though there has been limited research on the effects of fire suppression in boreal forests, it is reasonable to expect an increase in fuel hazards in regions where fire suppression has altered the fire regime (Omi & Martinson, 2004). Woods and Day (1977) conducted a fire regime study of Quetico Provincial Park and found a substantial increase in fire return interval, from 78 to 870 years. Therefore it is reasonable to believe fuel hazards may be of concern for boreal forests of this region (Ontario Ministry of Natural Resources (OMNR), 1993).

Boreal forests are generally characterized by large stand replacing fires. Fire extent is induced by horizontal and vertical continuity of fuels (Fernandes & Botelho, 2003). If fire suppression has limited the number and area burned of fires, it is reasonable to expect an increase in horizontal continuity of fuels and a shift from mixed species to more coniferous stands (Bergeron et al., 2001; Stocks et al., 1998). Therefore when large fires do occur they are likely to become even larger than prior to historical fire suppression.

A further consequence of suppression is the increasingly large proportion of forests succeeding into old-growth stands with conifers as the dominant vegetation (Bergeron et al., 2001; Hély et al., 2000). Old growth boreal forests are more volatile because of a shift from mixed fuels to more coniferous fuels (Hély et al., 2000), contributing to a higher level of flammability on the landscape, thus increasing the potential for large-scale catastrophic wildfires. As well, a shift in forest composition may lead to a variety of insect and disease problems (Gollberg et al., 2001), further altering forest composition and increasing the horizontal availability of flammable fuels (Suffling & Perera, 2004). Debate continues today regarding the regional impact of effective fire suppression during the past 80 years (see Miyanishi & Johnson, 2001; Ward, Tithecott & Wotton, 2001).

In North American by the early 1970's, fire suppression was reevaluated by fire managers, ecologists and natural resource planners, with the realization that fire was ecologically integral to ecosystem sustainability, particularly in the boreal forest (Woods &

Day, 1975). The United States fire management abruptly adopted wide-scale use of prescribed burns, demonstrating the policy shift to ‘black is beautiful’. This new fire paradigm was implemented to such a degree that area burned by prescribed burns was surpassing that of wildfires (Pyne, 1982).

Globally, many fire agencies have now adopted prescribed burning as a fire management tool in an attempt to allow fire to function as a natural disturbance process. However when fires threaten significant values at risk, full fire suppression tactics pre-empt consideration for natural processes (Gollberg et al., 2001). In addition to fire suppression altering historic fire regimes, operational fire suppression tactics may affect ecosystem structures and functions. These impacts are not always considered in operational fire management decisions, and are often difficult to separate from the ecological impacts of fire (Backer et al., 2004). Such considerations should include impacts on soil retention, species at risk concerns and water quality (Backer et al., 2004), hence many agencies developed an adapted fire suppression tactic called ‘light-on-the-land’ to reduce negative ecological impacts (Backer, Jensen & McPherson, 2004). Fire suppression is a necessary fire management strategy to ensure the protection of values at risk, however there is a need to balance traditional fire suppression techniques with other proactive techniques. As a history of fire suppression has lead to the accumulation of fuel hazards, suppression can no longer be the only viable fire strategy.

2.2 The Future of Fire Management: FireSmart Forest Management

With an increase in catastrophic wildfires and the expansion of the wildland urban interface, there is an increase in frequency and concern over interface fires. To combat the risks of interface fires, we must manage fires at a landscape scale and recognize that effective protection from interface fires cannot rely solely on good fire control (Partners in Protection, 2003). Traditional approaches to fire control are approaching the maximum effectiveness without addressing escaped wildfires (Hirsch et al., 2004), such as those experienced in Kelowna, British Columbia in 2003, resulting in significant loss of property (Filmon, 2003).

FireSmart community protection was developed by Partners in Protection, an Albertan based coalition of professionals representing national, provincial and municipal associations and government departments responsible for natural resource management and planning (Partners in Protection, 2003). The objective is to use fuel management in a proactive manner to reduce the area burned and risks associated with unwanted wildfires and prescribed burning strategies surrounding communities (Hirsch et al., 2004; Martell et al., 2004). FireSmart forest management aims to: 1) Decrease the potential landscape-level fire behaviour; 2) Reduce potential for ignitions; and 3) Improve fire suppression capability with existing resources (Bevers et al., 2004; Hirsch et al., 2004; Partners in Protection, 2003). The fire environment is assessed to identify fuel hazards and this knowledge is incorporated into strategic and operational fire management (Hirsch et al., 2004).

FireSmart forest management is one approach to address the threat of wildfires to communities. To combat the risks associated with wildfires, FireSmart forest management focuses on the prevention of fire spread through communities. The concepts behind FireSmart community protection are not entirely new, as far back as the 1950's forms of fire prevention focussed on the modification of the fire environment (Pyne, 1982). The FireSmart community protection program has formalized a simple systematic approach to protect areas of high values at risk from wildfire events through the reduction and isolation of fuels surrounding these values.

As crown fire is more likely in dense coniferous forests, a central component of FireSmart forest management is to create an environment with low stand density, scattered surface vegetation and absent or scattered *ladder fuels* in a 10 km zone surrounding a community (Partners in Protection, 2003). The landscape beyond this zone is not altered. This community-focussed approach does not reduce the potential of catastrophic wildfires within the surrounding landscape. However the concepts of reducing fuel continuity can be extrapolated from a community context and applied across boreal landscapes, to reduce the potential for catastrophic wildfires that are burning outside of historic fire regimes and threaten other values at risk, such as timber values, critical infrastructure, and other ecological values.

2.2.1 Fuel Management

As the fire environment is the main influence on the final size of escaped fires, focus should be on those aspects of the fire environment that can be actively managed (Hirsch et al., 2004). The three components of the fire triangle are fuel, weather and topography. Fuel is the only component that can be effectively managed and strongly influences fire behaviour (Fernandes & Botelho, 2003; Graham et al., 2004; Hirsch et al., 2004; Pollet & Omi, 2002).

The goal of fuel management is to make changes to the fuel complex to proactively modify wildfire behaviour and indirectly facilitate suppression efforts, thereby limiting wildfire sizes and severity (Finney, 2001; Finney, McHugh & Grenfell, 2005; Hirsch et al., 2004). To be successful at limiting fire behaviour and area burned, fuel management should decrease fuel hazards through the reduction of surface fuels, ladder fuels and crown density, while leaving some larger trees (Agee & Skinner, 2005; Loehle, 2004), or by converting from highly flammable to less flammable fuels (Partners in Protection, 2003).

The reduction of crown fuels is important as *crown fires* are more likely to develop into active crown fires (Graham et al., 2004), thus creating catastrophic wildfire events threatening values associated with the wildland urban interface, timber resource areas and protected areas (Graham et al., 2004). The complete elimination of crown fires is neither feasible nor ecologically desirable as they are a natural component of many disturbance regimes (Weber & Stocks, 1998). Limiting the extent and probability of these fires is important for public safety, resource protection and returning to historic fire regimes.

Fuel management can be broken down into three categories: fuel reduction, fuel conversion and fuel isolation (Martell et al., 2004; Pyne, 1984). Fuel reduction is achieved by reducing fuel loads by using periodic prescribed burns or thinning practices (Agee & Skinner, 2005; Martel et al., 2004). Fuel conversion is the replacement of highly flammable coniferous fuels, with less flammable deciduous fuels (Martell et al., 2004; Partners in Protection, 2003). This can be done through harvesting and/or prescribed burning followed by planting deciduous species. Fuel isolation aims to fragment fuels through the use of roads, cut blocks and fuel breaks, thereby reducing the vertical and horizontal continuity of flammable fuels (Fernandes & Botelho, 2003; Martell et al., 2004).

Typical fuel treatment types that can reduce fire rates of spread and intensities are prescribed burning and thinning, or a combination of the two (Agee & Skinner, 2005; Finney, 2001; Finney et al., 2005; Graham et al., 2004; Pollet & Omi, 2002).

For this research, methods of implementing fuel treatments are less relevant than the conceptual basis for landscape scale fuel treatments. Approaching fuel management from a landscape perspective is likely to have more success on overall reduction of fire spread, intensity, perimeters and suppression capabilities, than in comparison to the treatment of isolated forest stands (Finney, 2001; Graham et al., 2004). The spatial arrangement of fuels is critical in determining the growth of large fires (Finney, 2001; Graham et al., 2004; Loehle, 2004), therefore the spatial landscape pattern of fuel treatments and the forest is a significant factor in reducing area burned (Agee & Skinner, 2005; Fernandes & Botelho, 2003). This is because fire must burn around treated fuel patches, reducing fire intensity and rate of spread (Finney, 2001; Graham et al., 2004). If this occurs within a certain proportion of an active fire perimeter, the potential to substantially reduce area burned is increased. Possible key areas for intervention management are those landscapes that are composed of a mosaic of alternate stable states and that connect or fragment areas in the same alternate state (Peterson, 2002), such as boreal forests that are often a mosaic of varying patches of stand types and ages.

Landscape and plant heterogeneity will affect the extent of the fire. Breaks in topography, such as surface hydrology, rock outcrops and certain plant communities act as fire barriers, thereby increasing fragmentation of fire extent (Whelan, 1995). Though it is difficult to quantify changes in fragmentation, we can determine if fragmentation is increasing or decreasing. A study by Lefort et al. (2003) found that there is a likely correlation between decreased area burned and increased fragmentation in those areas that had been fragmented by agricultural development in Canada.

Strategic fuel breaks (a fire management method that reinforces existing defensible locations used to stop fire spread) is another fuel management technique (Finney, 2001; Graham et al., 2004). Strategic fuel breaks are usually easily accessible, inexpensive in comparison to random treatments and do help contain the fire perimeter. However the effectiveness of changing fire behaviour from within the fire is limited (Graham et al., 2004), and if the containment line is breached, the fire will continue to grow in size and intensity, requiring continual direct attack measures. These traditional fuel breaks are not effective in limiting the spread of crown fires (Loehle, 2004). Others researchers have suggested the idea of strategic fuel breaks (Hirsch et al., 2004; Finney & Cohen, 2003), and found that they slow fire spread, but would require more systematic application to be successful at limiting landscape level fire size (Loehle, 2004).

Using percolation theory (see Section 2.6.1), Bevers et al. (2004) studied the effects of *random* fuel treatments in simulated landscapes, with the hypothesis that a critical fraction of fuel fragmentation is needed to create a successful landscape-scale fuel break between wildland areas and development zones. They found that random fuel treatments would be needed throughout the majority of the forest to be successful. However in regions where long-distance spotting is common with extreme events, random disperse fuel treatments may be more effective than strategic and networked treatments at limiting fire growth by reducing ignition and growth potential (Fernandes & Botelho, 2003).

Loehle (2004) modelled the effect of random and strategic bulkhead fuel treatments on area burned using a cellular (percolation) model and found that a threshold does exist below which a landscape is essentially fireproof. Though the strategic bulkhead strategy was more effective than random treatments, at 25% area treated the random fuel treatments were comparable to the strategic bulkheads. At the 30% threshold the landscape could be considered theoretically fireproof, noting that these results were based on a conceptual study and therefore do not have prescriptive value. Another study in a ponderosa pine forest in Arizona found this threshold to be 18%. A lower percentage of treated area is possible if random treatments are concentrated in high hazard areas, such as coniferous fuels (Loehle, 2004). Fireproof should not mean that fire is completely excluded from the landscape, that instead fires are limited from becoming extremely large wildfires, thus allowing for natural and prescribed fires to burn more freely without fear of catastrophic events (Loehle, 2004).

The challenge for landscape level treatments is 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). We need to expand research from theoretical landscapes to realistic heterogeneous landscapes (Agee & Skinner, 2005), using socially and ecologically acceptable treatment methods in order to improve fuel management strategies.

2.3 Fuel Treatment Prescriptions

Prescribed burning and mechanical thinning are two options for fuel management prescriptions. Prescribed burning is the deliberate application of fire in fuels, under predetermined conditions in order to reach well-defined management goals (Fernandes & Botelho, 2003). Prescribed burning is less precise in comparison to mechanical thinning, and potential of fires escaping can make prescribed burning a politically sensitive decision for planners (Graham et al., 2004; Hirsch et al., 2004). Prescribed burns are effective in reducing fine fuels, duff, large woody fuels, rotten material, shrubs and other live surface fuels, thus drastically reducing fuel loads of treated areas (Finney et al., 2005; Graham et al., 2004; Fernandes & Botelho, 2003) thereby reducing flammable continuity of fuels and effectively reducing fire behaviour (Agee & Skinner, 2005; Fernandes & Botelho, 2003). 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.

More field research is needed on the effectiveness of prescribed burning fuel treatments (Fernandes & Botelho, 2003), as treatments might not be sufficient on their own to achieve structural goals of forest restoration, but are likely a good first step in assisting in the long-term reintroduction of ecological disturbances (Finney et al., 2005). To date there has not been a systematic field study of the effectiveness of prescribed burning as a fuel treatment in a fuels composition and structure similar to Northern Ontario. There are several in the Western United States and Australia that generally demonstrate prescribed burning is effective in reducing fire intensity and extent. See Fernandes and Botelho (2003) for a review of these studies.

Mechanical thinning is more precise and effective in reducing vertical fuel continuity, thus reducing ladder fuels and the fire hazard for 10 or more years (Agee & Skinner, 2005; Graham et al., 2004; Loehle, 2004, Fiedler & Keegan, 2003). However, thinning can increase the surface fuel load depending on the method of yarding (Agee & Skinner, 2005), causing increased intensities (Finney, 2001; Graham et al., 2004). 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 (Graham et al., 2004). These gaps allow for increased surface winds to carry an ignition (Omi & Martinson, 2004). 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 (Weatherspoon & Skinner, 1996). For this study, thinning was not modelled, as it is difficult to model forest thinning (i.e. fuel reduction) in comparison to fuel isolation and fuel conversion. For details on silviculture options for fuel treatment see Graham et al., (1999), Peterson et al., (2003) and Stephens (1998).

Fuel treatments have become controversial in the sense that some equate logging with fire as an ecological process or, more mildly, argue that thinning should precede fire. The assumption that forest thinning will help restore healthy forests is potentially flawed (Kauffman, 2004). The concept of reducing area burned through fuel treatments is not synonymous with thinning replacing fire as a naturally occurring landscape level process. This is important because though fuel treatments may take the form of thinning or other logging practices to reduce the potential for large wildfires, they should not be applied universally to reduce area burned throughout an entire region. Instead, these practices should only be used in those areas in which average area burned and intensity has increased beyond the historic range.

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 reducing fire behaviour (Graham et al., 2004), thus reducing area burned. Habitat quality may be threatened by fuel treatment prescriptions that alter the stand structure, though extreme wildfires generally have a more extreme impact on wildlife than fuel treatment prescriptions (O'Laughlin, 2005).

A combination of prescribed burning and mechanical thinning should be considered for those areas in which both methods are feasible and desirable (Graham et al., 2004). A study by Stephens (1998) found that multiple treatment type strategies were most effective in reducing rates of spread and area burned under 95th percentile weather conditions.

Multiple fuel treatments are usually required to maintain relative 'fire-proofing' of initial treatments, as fuels build up as stands age (Agee & Skinner, 2005; Finney, 2001; Finney et al., 2005; Hessburg et al., 2005; Loehle, 2004; Whelan, 1995), although an increased canopy base height usually persists (Agee, 2003). It is suggested that it is not the history of fuel treatments that determines fire behaviour, but instead time since last treatment and treatment size (Finney et al., 2005). The key to determining fuel treatment frequency is to understand the regional fuel and weather context including the historic fire regime and the rate of vegetation growth, which is affected by local climatic conditions, soils and nutrient availability (Fernandes & Botelho, 2003; Graham et al., 2004; Stephens, 1998).

Hirsch et al. (2004) suggest the following techniques as potential FireSmart forest management methods in active timber productive forests:

- Following natural fuel type changes, topography and hydrology for cut-block boundaries,
- Orienting cut-blocks according to the prevailing wind, and
- Prescribed burning to reduce fuel hazards in surrounding unproductive forests.

How to treat fuels will depend on the composition, moisture content, amount and structure (size, distribution, depth, and age) of fuels, as these factors strongly influence how they burn and in turn how the fire effects the environment (Graham et al., 2004). Altering the horizontal and vertical continuity of fuel strata can alter fire behaviour, and therefore understanding fuel conditions is key to developing fuel management strategies (Graham et al., 2004). Short- and long-term ecological, economic and social values should also be considered when determining fuel treatment potential (Finney, 2001; Graham et al., 2004; Hirsch et al., 2004).

2.4 Implications of a Changing Climate

The debate over the effects of anthropogenic climate change is heated, but understanding the reality of climate change is paramount to the future of Canadian boreal forests. It has been shown that human-induced climate change is likely altering fire regimes in Canada at various temporal and spatial scales, resulting in higher fire frequency, intensity and area burned (Weber & Flannigan, 1997). Understanding climate change effects on boreal forests is critical to the future of fire management planning. Three significant changes expected in boreal forest landscapes are: altered vegetation and landscape mosaics, altered fire occurrence potential, and changes in fire severity due to changes in the fire weather (Weber & Flannigan, 1997).

2.4.1 Probable realities of climate change

By the year 2100, it is estimated that the global mean surface temperature will increase by 1.1 to 6.4ºC (Alley et al., 2007), a change of magnitude and speed unprecedented in the past 10 000 years (Stocks et al., 1998; Weber & Flannigan, 1997). Though atmospheric temperature changes have occurred throughout geologic history, the recorded changes post industrialization indicate an anthropogenic origin (Weber & Flannigan, 1997). Gillett et al. (2004) found that human emissions of greenhouse gases and sulphate aerosol have contributed to global climate warming, and has had a detectable influence on area burned in the past four decades in fire prone areas in Canada. For a more detailed review of the impacts of human emissions of greenhouse gases and sulphate aerosols on detectable climate warming in North America see Lavender (1997), Zwiers and Zhang (2003), Allet et al. (2007) and Koroly et al. (2003).

Along with winter and springtime warming (Stocks et al., 1998), projections indicate a 20% variation in regional precipitation in summer and winter as well as drier summer soils with an average of 2-8 mm less water (Reinhard, Rebetez & Schlaepfer, 2005; Weber & Flannigan, 1997). A study by Reinhard, Rebetez and Schlaepfer (2005) found a decrease in cloudiness, causing an increase in sunshine hours thereby increasing the maximum temperatures, as well as decreasing precipitation in critical fire prone regions in southern Switzerland. This could result in longer fire seasons characterized by longer series of hot days without cooler interruptions, accompanied by greater precipitation variability due to an increased moisture-holding capacity of the warmer atmosphere (Overpeck, Rind & Goldberg, 1990).

2.4.2 Fire regimes in a changing climate

A fire regime integrates the influences of several fire behaviour characteristics, affected by weather, and landscape structure characteristics, expressed in the following components: fire frequency, size, intensity, seasonality, type (crown versus surface) and severity (depth of burn) (McLoughlin, 1998; Pyne, 1984; Weber & Flannigan, 1997; Whelan, 1995). Whelan (1995) describes the importance of these components and the interactions of the resulting fire regime with the landscape.

The forest structure and function, weather and climate strongly influence each fire regime component (Flannigan et al., 2000; Weber & Flannigan, 1997). In fact, fire regime responds very quickly to climate changes (Weber & Flannigan, 1997), because fire behaviour responds immediately to fine fuel moisture, which is affected by precipitation, relative humidity, air temperature and wind speed (Van Wagner, 1987). These factors can therefore be a limiting condition to fire growth or a primer for extreme wildfires (Flannigan, et al., 2000; Stocks et al., 1998).

Scenarios of 2 x CO2 levels have been used in GCMs to represent plausible changes in greenhouse gases in the next century, with most studies suggesting a higher occurrence of extreme weather events and regionally elevated temperatures (Flannigan et al., 2000). Therefore if climate changes projections are realized in the next century, the effects of altered fire regimes could be swift and far reaching across the boreal biome in Canada (Flannigan et al., 2000, Suffling & Speller, 1998). The interaction between climate change and fire regime has the potential to overshadow the importance of the direct effects of global warming on species distribution, migration, substitution and extinction (Suffling & Speller, 1998; Weber & Flannigan, 1997).

Climate changed fire regimes could be represented by a doubling of annual area burned by the end of this century (Flannigan, Stocks & Wotton, 2000; McCoy & Burn, 2005), because of an extended fire season, increased fire frequency and severity (Bergeron et al., 2001; McCoy & Burn, 2005; Weber & Flannigan, 1997; Westerling et al., 2006). Area burned has increased over the past 40 years, as noted by Van Wagner (1988), Skinner, Tocks, Martell, Bonsal and Shabbar (1999), Suffling (1992) and Podur, Martell and Knight (2002). Gillett et al. (2004) report that this is not an artefact of new technology such as satellite imagery.

In the long term, temperature is a good predictor for area burned as it is most easily observed (Gillett et al., 2004). Westerling et al. (2006) found that warmer fire seasons have resulted in a 600% increase in average area burnt and four times the fire frequency in the western United States. Studies have generally shown that an increase in fire has been occurring at higher elevations, however Westerling et al. (2006) found that summer drought is more intense and longer in duration at lower elevations. Regional projections show a likelihood of increased fire occurrence primarily in central and western Canada, potentially with decreasing occurrence in the eastern boreal area (Weber & Flannigan, 1997). However more detailed, regional modelling is required to substantiate these results. A study by Podur et al. (2002) determined that although part of the increase in Canada and Ontario can be attributed to the inclusion of new protected areas, this is not the situation for the increase in fire occurrence for a case study northwest of Quetico Provincial Park. The increases in fire activity may be attributed to other influences, such as climate change and other land uses changes. However due to absence of complete data, disentangling the effects of historical fire suppression and climate change was difficult (Podur et al., 2002). Munoz-Marquez Trujillo (2005) found in the comparison between climate change scenarios between 2010 and 2060, the frequency of fires in North-western Ontario will slightly decrease though area burned will increase substantially, possibly indicating a greater frequency of extreme wildfires.

Flannigan et al. (2000) found that with an increased *seasonal severity index,* annual area burned would increase by 25-50% in the United States by the middle of the 21st century. Wotton and Flannigan (1993) also found that the fire season lengths will likely increase by 22% or 30 days longer in Canada with an earlier annual start and end (Flannigan et al., 2000). In the western United States, Westerling et al. (2006) studied historical data from western United States and found that the average season-length increased by 78 days, mainly due to earlier ignitions in the spring and later end to the fire season. These results cannot be applied universally across the US or Canada due to the coarse spatial and temporal resolution of the GCMs and due to regional variability; therefore regional climate models should be used (Flannigan et al., 2000; Weber & Flannigan, 1997).

GCMs, paleo-evidence of fire regimes as they relate to climate change, ecological modelling and fire simulation modelling separately have limitations, leaving uncertainty about the future of fire regimes in Canada under changing climatic influence. In order to resolve the shortcomings of any one method alone, a boreal forest open-air experiment is needed, combining field plots/greenhouses, outdoor microcosm, growth chambers and modelling components, similar to the Jasper Ridge CO^2 experiment by Field, Chapin, Chiariello, Holland and Mooney (1996) (Dale et al., 2000; Weber & Flannigan, 1997). Field experiments are time consuming, very expensive and often not feasible. Therefore fire and forest management should proactively address the potential of climate change effects through computer fire growth modelling and begin to address the likely implications on fire frequency and intensity.

2.5 Fire Simulation Modelling

Given the complexity of fire variables such as weather, fuels, fire behaviour, and land use patterns across scales (Gardner, Romme, Turner, 1999; Keane et al., 2004; Richards, 1994), there has been greater interest in computer simulation models for fire management and planning in Canada in recent years. They complement empirical evidence of fire history reconstruction, such as dendrochronological studies, and provide insight into the dynamics of ecological systems (Boychuk & Perera, 1997). Simulation modelling is needed to build effective fire management planning and decision-making beyond fire history construction (Suffling et al. 2003). It is important to recognize modelling as a tool to aid fire managers in assessing fire management strategies, but should not be used to replace local knowledge. Fire models are useful for assessing the range of conditions under which fuel treatments can modify fire behaviour (Graham et al., 2004).

Different simulation models are used for different case studies because of limited knowledge of physical and chemical processes in wildfires and cross-scale variation in natural fuel beds, topography, local to micro scale climatic conditions (Perry, 1998). With this in mind, modelling can be best described by category.

One approach to categorization is to examine the mathematical basis of models. Most commonly, models could be defined as deterministic or stochastic models and spatial or non-spatial models (Perera & Baldwin, 2000). Deterministic models usually examine a single fire event for the duration of that fire. Stochastic models focus on multiple fire events over long timeframe (He & Mladenoff, 1999), and therefore account for inherent variation in process and predict outcomes of known probabilities (Perera et al., 2003).

In some cases, deterministic models can provide reliable results for site-specific conditions over a short time period, but generally become less reliable over larger spatial and temporal landscapes (Hargrove, Gardner, Turner, Romme & Despain, 2000; He & Mladenoff, 1999). Rothermal (1972) is the basis for many deterministic models, and focuses on the estimation of fire behaviour characteristics, such as rate of spread. Deterministic models require hourly and site-specific data inputs, such as fuel conditions, weather and topography, using mathematical equations to analyze and link the physical environment and disturbance under study (Hargrove et al., 2000; He & Mladenoff, 1999). These models are potentially problematic if the goal is to predict broad-scale spatial patterns of large fires over longer time periods (Hargrove et al., 2000), due to the necessity to extrapolate short-term findings from site-specific scenarios to the long-term and large-scale.

Stochastic models combine random number generators and probability distributions to simulate forest fires, where most are based on Johnson's (1992) summary of fire frequency and probability theories (see He & Mladenoff, 1999). These models are capable of examining how fire disturbances are an important source of forest heterogeneity at broad scales and the relationship between fire regimes and landscape structure overtime (He & Mladenoff, 1999). Stochastic models are not capable of predicting daily fire spread, but rather focus on predicting the final pattern and broad-scale heterogeneity of a fire (Hargrove et al., 2000).

Non-spatial models are physical and semi-physical models that study the physics and thermodynamics of fire behaviour. Spatial models focus on the prediction of final shape of a forest fire (Perera, Baldwin, Schnekenburger, Osborne, & Bae, 1998; Perera et al, 2003). Spatially explicit models use geo-referenced inputs and produce geo-referenced outputs (Perera et al, 2003). GIS and remote sensing have significant potential for the evaluation of fire danger and the predictive modelling of the spatial behaviour of fire (though comparatively little research has been done on this subject) (Perry, 1998). Spatial resolution for modelling will continue to cause some difficulties in fire growth modelling. A fire simulation model must function at a grain size which is fine enough to capture local variations of the fire environment, while still predicting fire spread at broad spatial scales (Hargrove et al., 2000). Models can only be as good as the quality of input data.

The Canadian Forest Fire Danger Rating System (CFFDRS)

Understanding the Canadian Forest Fire Danger Rating System (CFFDRS) system and associated sub-systems is relevant for fire modelling within Canadian landscapes. This is because a good working knowledge of how the fire environment affects fire growth is critical to simulating realistic fires using a fire growth model. The CFFDRS, originally issued in 1970, is a conceptual model for fire danger assessment that was derived from the earlier work of J.G. Wright and his colleague H.W. Beall beginning in 1925 (Van Wagner, 1987). This system can be broken down into two main components: the Fire Weather Index (FWI) and the Fire Behaviour Prediction (FBP) System (Van Wagner, 1998).

The essential purpose of FWI system is to provide a series of relative indices of fire potential based on a standard pine fuel type, but has been used successfully as a measure of fire danger across Canada (Van Wagner, 1987). It describes various weather conditions that can be translated into fuel moisture codes and indices, which are essential in the use of fire modelling programs (Li, Flannigan & Corns, 2000). The system is based on the moisture content of these three classes of forest fuels and the effect of wind on fire behaviour (Van Wagner, 1987). The fine fuel moisture code (FFMC), the duff moisture code (DMC) and the drought code (DC) represent daily changes in the moisture content of these classes of forest fuels, as each has different drying rates (Van Wagner, 1987). The system relies on daily weather readings of dry bulb temperature, relative humidity, 10-metre open wind speed and 24-hour accumulated precipitation from noon local standard time (LST), but represents the afternoon burning peak of approximately 1600 hours (Van Wagner, 1987). Van Wagner (1987) describes the fuel moisture codes, sub-indexes of the FWI System, as:

1. FFMC: Represents moisture content of litter and other cured fine fuels in a forest stand.

2. DMC: Represents moisture content of litter and decomposing organic matter.

3. DC: Represents deep layer of compact organic matter.

The effects of wind and the fuel moisture codes are combined in pairs to build three indexes of fire behaviour: 1) Initial Spread Index (ISI), a combination of wind and FFMC to representing a numeric rating of rate of fire spread; 2) Buildup Index (BUI), a combination of DMC and DC that represents total fuel available for combustion; and 3) FWI component that represents potential intensity of fire on flat terrain for the standard mature pine fuel type (Van Wagner, 1987; Forestry Canada Fire Danger Group, 1992). For greater detail on the FWI system see Van Wagner (1987).

The second major sub-system of the CFFDRS is the Fire Behaviour Predication (FBP) System. This system, published in 1992, was tested against experimental fires, including the largest crown fire data set, and against well-documented wildfires (Forestry Canada Fire Danger Group, 1992). This system helps operational fire managers assess daily fire hazards. There are currently 16 benchmark fuel types used in the FBP System (Appendix C). The FBP System provides quantitative estimates of potential forest fire behaviour including head fire spread rate (in m), fuel consumption (in kg/m^2), and fire intensities (in kw/m) for flank, back and head fires and descriptions (Forestry Canada Fire Danger Group, 1992). Coupled with a simple elliptical fire growth model, FBP can estimate fire area, perimeter, perimeter growth rate, and flank and backfire behaviour for homogeneous landscapes (Forestry Canada Fire Danger Group, 1992). The three-fuel moisture content codes area used, especially the FFMC, to calculate one of the primary products of the FBP system, the rate of fire spread (ROS) (Forestry Canada Fire Danger Group, 1992).

Fuel conversion is the second concept under study in this research. Therefore accuracy of fire spread in mixed-wood fuel types is critical to the reliability of the results of this research. The Fire Behaviour Prediction (FBP) system calculates fire spread in mixed-wood fuel types based on conifer and dead fir percentage content, which guides how the fire behaviour characteristics of boreal spruce and leafless aspen are combined. As the FBP system is the basis for Prometheus, and the best method of classifying fuels in Canada, this research will not attempt to alter the FBP component of Prometheus. .

2.6 Conceptual Model Theories for Fire Growth Simulations

Fire growth simulation models can be classified into either cellular or vector approaches (Finney, 1999). In turn, these can be divided into elliptical, cellular automata (percolation), fire propagation in arrays, Markov chains, stochastic contagion, chaotic or wave propagation approaches. The two main modelling theories I will focus on are cellular automata (CA) or percolation, and wave propagation modelling, as they are the two main modelling approaches used in fire growth modelling today for research purposes.

2.6.1 Cellular Automata and Percolation Theory

Exploring cellular automata (CA) models helps us to understand the progression of fire growth modelling. CA models are dynamic, with discrete operations in time and space, on a uniform, regular grid and characterized by local interactions with nearest neighbours in previous or present time steps. For fire modelling, each cell represents a fixed surface area and has attributes that correspond to the fire environment, e.g. fuel type or topography (Bodrožić, Stipaničev & Šerić, 2006). The majority of current fire growth models for research are based on CA, and therefore understanding the advantages and disadvantages of some of the models is useful in determining the effectiveness of modelling fire environments. Different approaches of empirical simulation models, such as cellular automata grid systems based on percolation theory, are capable of predicting rates of spread and fire perimeter position for a spatially and temporally variable fire environment (Richards, 1994). These models use sophisticated computer-based simulations of fire behaviour, such as the analytical elliptical fire shape model.

Percolation theory is the basis for cellular automata modelling methods. Percolation theory stems from mathematical physics that describes how a fluid propagates through a medium affected by the fluid (Redsun, 2006). Applied to forest fires, a fire can move through a landscape by spreading from one patch of fuel to another (Green, Tridgell & Gill, 1990). This assumes that there is a path joining the patches and connected by a sequence of points to allow for fire spread, and can therefore be viewed as a percolation process (Green et al., 1990). Fire spread depends on a critical density of available fuel in the landscape. The rate of spread changes in relation to variation in fuel continuities and types, weather and spatial scale (Green et al., 1990).

Though there are several techniques for modelling fire growth using cellular automata, generally cellular models use fixed distances between evenly spaced cells to determine the fire's arrival time between cells (Finney, 1999). This can limit the use of cellular models to predict fire growth shape and size in heterogeneous landscapes (Finney, 1999). By determining the forward rate of spread (rate of spread in the direction of the wind), it is possible to predict the size and shape of a wildfire. Growing from the ignition point, a fire spreading within spatially homogeneous fuel and uniform terrain achieves an elongated ellipse under the influence of the wind. As the fire encounters alterations in fuels, topography and microclimatic conditions, localized changes in the rate of spread occurs causing changes to its shape (Perry, 1998).

One difficulty with CA is that distortion of fire shape can occur as there are only a fixed number of directions to spread, and the effects of temporal variation from environmental variables, such as weather and wind because the fire perimeter is not continuously represented (Perry, 1998). Reducing distortion might be possible by enlarging the search radius for interacting cells and decreasing the time step (Perry, 1998). However, fire shape distortions may still result depending on the specific underlying algorithm used (Perry, 1998). French, Anderson and Catchpole (1990) compared the strengths and weaknesses of a number of CA models. Many of the concerns associated with CA models that area based on percolation theory have been addressed by the creation of wave propagation models. Since the 1990's, there have been advancements in raster based modelling approach. With finer resolution rasters, it may be possible to better represent local conditions. A recent unpublished study compares fire shape between raster-based CA models and wave propagation models, which have shown that the raster approach, even with great resolution, are not as realistic as wave models (B.M. Wotton, pers. comm., 2007).

Cellular Automata Applications

LANDIS, the Boreal Forest Landscape Dynamics Simulator (BFOLDS) and FIREMAP are examples of probabilistic CA fire spread models. These models rely on user-defined set of transitional probabilities between the cells; therefore they can define the probability of fire spreading from one pixel to the next (Anderson et al., 1998). These types of CA models were designed to explore one or more specific parameters at various spatial and temporal scales associated with the forest fire. However there is difficulty in predicting landscape scale effects of fire because of the fine-grained interactions between fuel, topography and weather (Gardner et al, 1999; Hirsch, 1996).

LANDIS explores landscape disturbances over a long-term period (i.e. 100 years) in forested landscapes, initially focussing on spatial disturbances such as forest succession, wind and fire (Mladenoff, 2004). LANDIS uses a repeating cycle of processes that operate on an initial input map and resulting time steps, using a raster GIS format (Mladenoff, 2004). LANDIS is frequently used to examine ecological theories, but can be used operationally due to the capability of using it in many geographic locations (Mladenoff, 2004).

The Boreal Forest Landscape Dynamics Simulator (BFOLDS) uses fire disturbance and vegetation succession models to explore the influence of disturbance on landscape dynamics. BFOLDS simulates fire over time using input from FBP and ignition probabilities that are calculated using a Poisson distribution with a mean variance of historical lightning occurrence for each day.

FIREMAP was developed using CA based on Rothermal's fire equations and combined them with raster fuel and topographic data to calculate the burning characteristics for each cell at each time step (Gardner et al, 1999). It was designed to predict fire behaviour in spatially non-uniform environments (Perry, 1998). Unfortunately it does not represent the stochastic nature of forest fires by not incorporating environmental variability. FIREMAP highlights the difficulty associated CA models as fire can only spread in the eight directions from the fire front cell (Gardner et al, 1999). For a review of CA models see Gardner et al. (1999).

2.6.2 Wave Models

Wave models, or vector models, are the latest in the types of spatial fire simulation models. Understanding the development of these models is critical to this research as. Vector models avoid problems associated with cellular automata models when calculating fire growth in spatial and temporal heterogeneity (Finney, 1999). Wave models explore more complex aspects of fire behaviour on the landscape by using differential equations based on Huygens' Principle, a series of equations first proposed by Anderson et al. (1992) for the simulation of wildfires graphically (Anderson et al., 1998; Hargrove et al., 2000; Richards, 1994). These models estimate the position in time of a fire perimeter for variable fuel and weather conditions (Richards, 1994). This function of position in time is based on estimates of equilibrium forward, flank and back rates of spread, which result in fire propagation of elliptically shaped fire perimeters (Hargrove et al., 2000). Wave models incorporate local variations of fuels and weather, possibly igniting many adjacent pixels in the same time step. For an in depth review of the mathematical principles and equations behind wave models see Richards (1994) and Finney (1999).

The ellipse is the most commonly used fire shape for wavelet propagation, as it is mathematically simple and fits most empirical fire shape data (Finney, 1999). Other basic shapes proposed are ovoid, egg-shaped or double ellipsed (Finney, 1999). Richards (1994) studied a variety of fire shapes used for estimating fire spread and determined fire shapes tend towards the simple ellipse in landscapes with relatively uniform fuels, and without significant shifts in wind velocity. This coupled with negligible advantages of using more complex fire shapes (Finney, 1999), has made the ellipse the shape of choice for fire prediction and spatial growth simulation models.

The simple ellipse can be used manually to calculate fire spread in constant environmental conditions (Finney, 1999). However, as environmental heterogeneity and time since ignition increases, complex simulation methods are required to capture the spatial patterns of fire growth (Finney, 1999).

Wave models provide more realistic results for heterogeneous forests because the fuel, weather, topography at each vertex is incorporated, varying the shape and size of each new elliptical wavelet (Finney, 1999). Simulation models must reflect the different fire behaviour characteristics that arise with surface, ground or crown fires, such as the rate of spread for active crown fires due to the abundance of finer fuels.

A key problem is wave models tend to over predict the fire’s behaviour weather, which can complicate the accuracy of the simulator (Finney, 1999) particularly with smaller fires (i.e. under 10 hectares). Wave models can be computationally intensive (Hargrove et al., 2000). As well, models are not currently capable of incorporating micro-climatic conditions created by the fire itself; therefore models fail to capture some of the more subtle aspects of fire behaviour (Finney, 1999). However, deterministic wave propagation fire growth models, such as Prometheus, have been successful at predicting fire growth patterns in the Canadian boreal forest environment.

Wave Model Applications

FARSITE is a spatial fire growth model that integrates fuels and topography with weather and fuel moisture data, therefore providing managers the capability of analyzing fuel changes under specified ignition and weather scenarios (Fernandes & Botelho, 2003). FARSITE expands the fire front in two dimensions with the fire perimeters being processed and stored in vector format, while using raster data to represent the underlying landscape (Finney, 1998). This model is useful in the United States as it incorporates surface fire, crown fire, spotting, fire acceleration, and fuel moisture while allowing for the use interactive suppression tactics (Perry, 1998). Using FARSITE to examine fire growth modelling in a Canadian context is not ideal as it is based on fuel and fire complexes found in the United States. FIRE!, developed by Green, Finney, Campbell, Weinstein and Laudrum (1995) uses the vector approach, where the fire front propagates like a wave, shifting and moving continuously in time and space (Perry, 1998). It is a GIS based model that uses the FARSITE fire spread model of Finney (1993) (Perry, 1998). It was created to better model spotting and torching predictions, but as it also based on US fuel types, it is not necessarily applicable in a Canadian context.

The Canadian Wildland Fire Growth Model (CWFGM) Prometheus was developed in response to this need for a Canadian specific fire growth model. It was designed to simulate fire growth using the FBP and FWI sub-systems of the CFFDRS and algorithms developed by Gwynfor Richards at Brandon University based on Huygens' principle of wave propagation (CWFGM Project Steering Committee, 2006). The underlying mathematical and geometric template for fire growth is the simple ellipse, opposed to a double ellipse or egg shape. Scientific review of Prometheus is difficult at this time as it is the only Canadian wave fire growth model propagation model. However, the foundation components of the model have been tested. The Fire Weather Index (FWI) System and Fire Behaviour Prediction (FBP) System components of Prometheus have been validated against the source code provided by the Canadian Forest Service. These findings will be published as part of the Prometheus Technical Document as a Canadian Forest Service report later in 2007. Field validation is ongoing through cooperation with external fire management agencies, and there is hope to publish this material at a later date.

Prometheus is capable of modelling three fire types: surface, ground and crown fires. Surface fires burn surface litter, such as grasses, forbs and shrubs. Ground fires burn the duff and organic material in the soil beneath the surface litter. Crown fires burn the crowns (tops) of trees or shrubs (Fuller, 1991). A fourth type of fire behaviour is intermittent crown fire, which switch between crown and surface fire behaviour.

Four specific objectives of Prometheus as outlined by the CWFGM Project Steering Committee (2006) are:

1. "Predicting the hourly or daily real-time growth of fires that have escaped initial attack";

2. “Evaluating the potential threat of wildfire to values-at-risk (e.g., communities, recreational facilities, timber management units, etc.);
3. “Assessing the effectiveness of management strategies aimed at reducing wildfire threat of large fires”; and
4. “Evaluating the risk of loss (or probability of wildfire) across landscapes altered by different forest management strategies and practices”.

Prometheus has the flexibility to model diurnal weather and allows for interactive modification of fuels and weather data, thus making it useful as a fire operational as well as a fire-planning tool. It runs on a desktop and is free of charge to any user. It uses grid ASCII raster data as the underlying input (CWFGM Project Steering Committee, 2006), yet the final fire shape is affected by the pixel resolution chosen by the modeller. Finding a balance in the resolution is critical to the question being asked of Prometheus. A standard pixel size cannot be determined, as each case study will require emphasis on different landscape features, thus determining the resolution. The pixel size will also be based on the detail available from the input data. Pixel size also indirectly determines computation time through the function of a fire engine setting, the *distance threshold*. This threshold determines the distance between fire ellipse calculations.

The quality of weather data is critical to the accuracy of Prometheus to grow fires under variable weather in a site-specific location. The usefulness of fire growth simulations is partially a function of the accuracy of weather input data. For best results, weather stations should be located in as close proximity to the study site as possible, to reduce the effects of terrain and meteorological differences as a function of distance on fire growth. It is also possible to create hypothetical or forecasted weather streams interactively within the user interface, making it potentially a useful tool for fire operation and planning. A weather stream is a term that is used in fire modelling to indicate a period of time defined by a stream of hourly weather data. Overall, as the foundation for Prometheus is the Canadian Forest Fire Behaviour Predication (FBP) System, and due to inherent built-in flexibility, Prometheus is an excellent fire growth model option for continental southern boreal forests. For a complete review of the programs capabilities and requirements see CWFGM Project Steering Committee (2006).

It was necessary to use an associated batch program for this research in order to simulate multiple fire iterations in a reasonable timeframe. BURN-P3 is a recently developed program that uses Prometheus as the fire growth engine to map burn probability (or wildfire susceptibility) for fire prone landscapes (Parisien, Kafka, Todd, Lavoie & Maczek, 2005). It is capable of simulating the growth of large escaped fires (>200 ha) typically found in Canada. This means that the model excludes the more numerous small fires, creating a more effective approach for landscape-scale fire modelling (Parisien et al., 2005). The model consists of three sub-modules: the ignitions module, the burning conditions module, and the fire growth module. The ignitions and burning conditions modules are probabilistic as derivatives of historical data in the form of frequency distributions (Parisien et al., 2005). However, there is a deterministic component to BURN-P3, due to the fact that the fire growth module is based on fire spread empirical equations from the FBP system (Parisien et al., 2005). As BURN-P3 is largely a probabilistic model, as the number of iterations increases, the more likely the outputs will fit within the frequency distributions of the ignitions and burning conditions modules. The multiple iterations (500-

1000) are done in a Monte Carlo fashion; thereby providing assessments of wildfire susceptibility based on static landscape conditions (Parisien et al., 2005). The final output is a cumulative map of area burned. Therefore this model cannot be used to examine the characteristics, including fire extent, of individual fires.

The recently developed Pandora is a Microsoft Windows based stand-alone executable that provides fire growth modellers the option of bypassing the Prometheus user-interface when faced with the possibility of running numerous Prometheus simulations. It was developed by the by the Canadian Forest Service (CFS) with support from Alberta Sustainable Resource Development. The user interface consists of is a single dialog box, where the user specifies the parameters file name, and where progress information is displayed (Englefield, 2006).

The basic required and optional data inputs are the same as in Prometheus, but these parameters are simply specified in a single text file, including the locations of the data input files (e.g. weather, fuels, terrain). The required input fields are: a fuels raster file, a weather stream file, a parameters file, and a projection file. Optional inputs are: fuel type lookup table, elevation, slope, aspect and ignition shape file. Pandora is capable of outputting fire perimeters in ESRI shape file format, and FBP components such as fire intensity and spread rate (Englefield, 2006).

Pandora can be accessed by other applications, thus simplifying potential multi-model capabilities. However, it does require a Prometheus COM licence, which is available upon request. As Pandora can simulate an infinite number of fires, its primary uses are for modelling fires as a batch process, and longer-term fire planning projects. Pandora does not offer the complete set of options of Prometheus, but it does provide a batch process for those modellers interested in multiple fire iterations (Englefield, 2006).

Some of the useful features Pandora currently offers are user specified grass curing %, the time step interval, burn period settings, angle and distance thresholds for calculating the fire perimeter, the method for calculating the hourly FFMC, a log file of all outputs, as well as offering single or multiple ignitions (Englefield, 2006).

2.7 Justification of Fire Growth Simulation Model

The choice between cellular automata or wave propagation models was easily made because CA models have difficulty predicting fire shape and size in heterogeneous landscapes (Finney, 1999) as they generally use fixed distances between evenly spaced cells to calculate fire spread and therefore do not incorporate fine-grained interactions between fuel, topography and weather (Gardner et al, 1999; Hirsch, 1996). Furthermore, though BFOLDS is a useful model for Canadian boreal fuels, running it requires extensive knowledge of the modelling procedures, and specialized computer equipment. As it was created for very large landscapes, approximately three times the size of Quetico Provincial Park, BFOLDS is not a valid option for this research (Perera et al., 2003).

Wave models provide more realistic results for heterogeneous forests because the fuel, weather, topography at each vertex is incorporated, varying the shape and size of each new elliptical wavelet (Finney, 1999). FARSITE and Prometheus were considered for this research.

FARSITE is a useful model in the United States as was designed for typical surface fire, crown fire, spotting, fire acceleration, and fuel moisture based on characteristics of American fuels and fuel classification systems. FARSITE and Prometheus are very similar models, with the main difference being the fire behaviour predication system used at systems' cores: FARSITE relies on the US BEHAVE System, and Prometheus relies on the Canadian FBP System. Using FARSITE to examine fire growth modelling in Canadian forest types is not ideal, though not impossible.

Prometheus was chosen as the model as it was designed to simulate fire spread across Canadian landscapes for both strategic and operational applications. It allows the user to test large wildfire mitigation strategies (CWFGM Project Steering Committee, 2006).

Prometheus relies on the FBP fuel system, which can provide some drawbacks when attempting to accurately represent site conditions with fuels that do not fit within the categories. Interest has been shown in creating new fuel types, however these would need to be field tested for accuracy. This research is not concerned with the exact representation of conditions found in Quetico Provincial Park, but rather a realistic mosaic of fuels.

Model validation is often difficult as most fires in Ontario have been subject to effective fire suppression. Validation against a set of real fires has been begun for Prometheus, however to date have not been formally documented, though it appears to be a good representation of fire growth in heterogeneous fuels (CWFGM Project Steering Committee, 2006). However Prometheus faces the difficulty of over-prediction of fire spread, a characteristic common to all fire spread models. The modelling community has not established methods to address this limitation. However, it is possible to use operational fire behaviour knowledge to tailor weather data inputs to more accurately represent periods of fire growth, and eliminate hours in the weather stream that realistically represent times of little to no fire growth.

Overall, Prometheus is the best wave model for this research as it is based on the Canadian FBP System for the predication of fire behaviour. In order to simulated multiple iterations, two batch programs were considered: Burn-P3 and Pandora. A batch process was necessary in order to the tens of thousands of simulations that were necessary for statistical rigour.

Burn-P3 is a user-friendly model that is capable to examining fire on a landscape scale and has been used in Canadian boreal fuels, as it relies on the Prometheus fire growth engine and more fundamentally on fire behaviour predications made using the Canadian FBP system. However, as it is mainly a probabilistic model with a final map- based on a summary of multiple fire iterations, it is not appropriate for this study. This research requires the capability to look at the final area burned for each individual fire in order to statistically compare the differences of fuel treatments on final area burned. Also, as Burn-P3 assumes small fires are easily suppressed, it eliminates these fires from calculations, and therefore does not account for the influence of all fires on the landscape. Though large wildfire events, not small fires, are the focus on this research, the ability to include small fires in the final analysis, is necessary to determine if fuel treatments significantly reduced fire extent of each fire. Therefore BURN-P3 was not a valid option.

Pandora is a batch application created to access Prometheus through the backdoor (Englefield, 2006). Though Prometheus has been used to manually run thousands of iterations using a network of computers (see Doran, 2004), the vast equipment needs make this an unrealistic option. This research was the first beta-test for Pandora, which meant some difficulties arose in getting the first successful batch process running. It also meant that I was able to work with the programmer to request certain options be available within the program, making the process an informative and instructive experience.

2.8 Literature Review Summary

From this literature review, we can conclude that area burned will likely continue to increase in the boreal forest due to more catastrophic wildfire events. This increase is occurring due to an accumulation of fuels from effective fire suppression, and longer and more severe fire seasons as a result of climate change. This poses a significant problem for fire management planning, as catastrophic fires are difficult to suppress and therefore threaten a wide range of values at risk. An increased frequency of these events would further alter fire regimes outside of the range of natural variability. Fuel management is one approach to mitigate the potential for catastrophic wildfire events. Fuel isolation (fragmentation) and fuel conversion applied randomly across a landscape could reduce area burned by reducing fire behaviour and creating effective fire barriers scattered throughout the boreal landscape. The conceptual hypothesis is that random fragmentation of highly flammable fuels could reduce area burned substantially. If implemented across many landscapes, this strategy could protect communities, timber resources, recreation and ecological values. Fire growth modelling can be used to test this theory and determine the percentage of a landscape needed to substantially reduce the average area burned. Modelling is a powerful tool when reliable and high quality data are used, and combined with operational and experimental knowledge of fire behaviour. After considering the fire growth models FARSITE, and Prometheus, I chose to use Prometheus for this research through the batch program Pandora.

Chapter 3
Site Description

3.1 A boreal forest case study

The boreal forest biome is one the world's two largest forest belts, covering approximately three billion square kilometres (Payette, 1992). In North American boreal forests are floristically poor, being dominated by one of nine tree species with dense under-canopies, with usually only one or two species dominating each forest (Payette, 1992, Shugart, Leemans & Bonan, 1992). Generally, nutrient availability is low and reoccurring disturbances are common, including stand-replacing fires (Bonan, 1992), wind-throw events, insect infestations and logging operations.

The boreal forest is the largest forest region in Canada, occupying approximately 315 m ha. Fire is a necessary catastrophic process releasing and redirecting nutrients including seed dispersal and is essential for natural renewal of boreal forests. The boreal forest fire regime would have included large, high intensity, stand-replacing fires that returned every 20-100 years on average, depending on stand type (Suffling, 1992; Woods & Day, 1977). In Canada, the long-term average annual area burned is 1.3 m ha, with extreme fire years being common, covering up to 7 m ha in a single fire season (Weber & Stocks, 1998). Only 2% to 3% of those fires cover more than 200 ha but contribute about 98% of the total area burned annually (Weber & Stocks, 1998).

Boreal forests have similar temporal succession patterns after disturbance; therefore the landscape patterns appear similar in gross appearance globally, but exhibit regional and local variations (Shugart et al., 1992). Studying regional landscape patterns is of value to theoretical development of fire management strategies; however findings must be adjusted to the site-specific context. This research focuses on Quetico Provincial Park to test fuel fragmentation and conversion concepts, but the methodology could be extrapolated to other boreal forest regions worldwide.

A provincial park was used for two reasons. Firstly, provincial parks frequently encompass large landscapes. It is difficult to locate a site with a continuous natural landscape, as industry, communities and other infrastructure fragment much of the boreal forest ecotype. Secondly, Ontario Parks as an organization has well documented the natural and cultural influences on many of their parks.

Quetico Provincial Park is a useful case study site because: 1) The landscape is a large, relatively continuous tract of natural ecosystems; 2) It is managed by one agency: Ontario Parks; 3) It is surrounded by large expanses of forests managed as protected areas, crown land, timber parcels and private property. If an extreme wildfire were to escape the park, it could threaten the variety of values at risk within this landscape; 4) The park is mandated to reintroduce fire into the park management planning and is unique in its proactive approach within the Ontario Parks system, thus potentially allowing experimental fire management strategies.

3.2 Quetico Provincial Park

Quetico Provincial Park, established in 1913, is a wilderness park of 476 000 ha, 160 km west of Thunder Bay. It is the third largest wilderness park in Ontario. Quetico is surrounded by crown land that is actively affected by timber harvesting, the Boundary Waters Canoe Area Wilderness, crown land and La Croix First Nation (Proescholdt, Raposon & Heinselman, 1995). See Figure 3.1 for regional context.

The park is a beautiful wilderness class park, comprised of a myriad of lakes and rivers, making it a canoeist's paradise. With the combination of wildlife, waterfalls and breath-taking vistas, this protected area is a perfect destination for all nature enthusiasts. The park also offers car camping, a visitor's centre and trails in the developed portion of the park.

Ontario's provincial policy suggests that fire should be re-introduced into fire-dependent systems in order represent natural heritage values (OMNR, 2003). The re-introduction of fire is a significant resource management concern. However, balance is needed between the needs of recreational users, appropriate conservation targets and an agreement of co-existence with First Nations to protect their rights and values in management policies and boundary zone issues (OMNR, 2003).

3.2.1 Physiography

Quetico Provincial Park is a low plateau of modest relief, fragmented by many lakes and streams, steep cliffs and endless rock ridges (Heinselman, 1996). Throughout geological history, erosion, several historic volcanic events and the continental glaciers of the Pleistocene Era 10,000 years ago shaped the present landscape (Heinselman, 1996). As part of the Canadian Shield, the rocks are of Archaean age (OMNR, 1977). The major rock types are greywacke, siltstone, slate, granite, syenite, pegmatite and migmatite (OMNR, 1977).

The soils are largely glacial till (a mix of sand, silt and stones) and are generally low in nutrients, thus the diversity of plants and animals is low (Heinselman, 1996; OMNR, 1977). Soil ranges from a few cm deep on ridge tops to approximately 3 m deep at the bases of slopes and in the lowland depressions (Heinselman, 1996). The landscape is also dotted with eskers and organic soils from peat lands in the form of bogs, swamps and muskegs (Heinselman, 1996). The Steep Rock Moraine is a large terminal moraine, of more than 30 m high within Quetico Provincial Park continuing through into the Boundary Waters Canoe Area Wilderness (Heinselman, 1996).

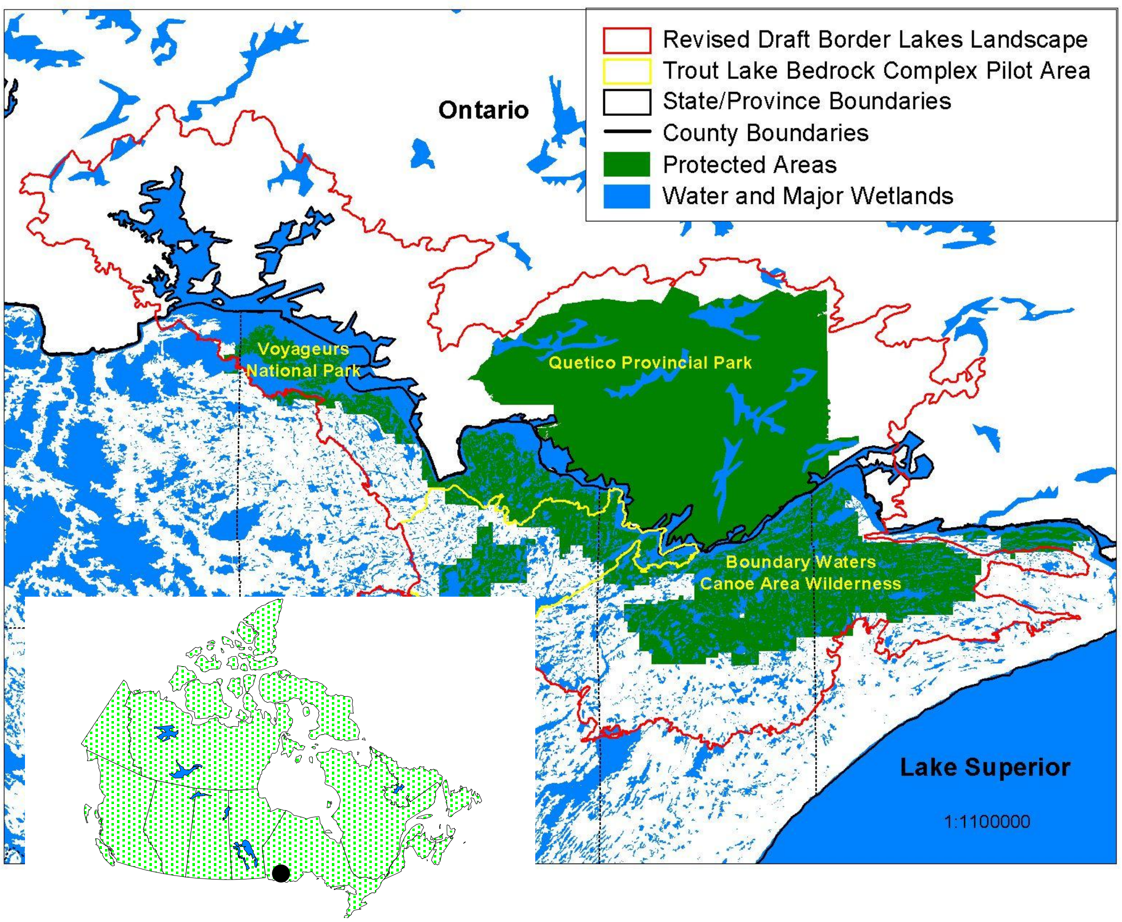

Figure 3.1 Regional context for Quetico Provincial Park. Author: Ontario Ministry of Natural Resources, n.d.

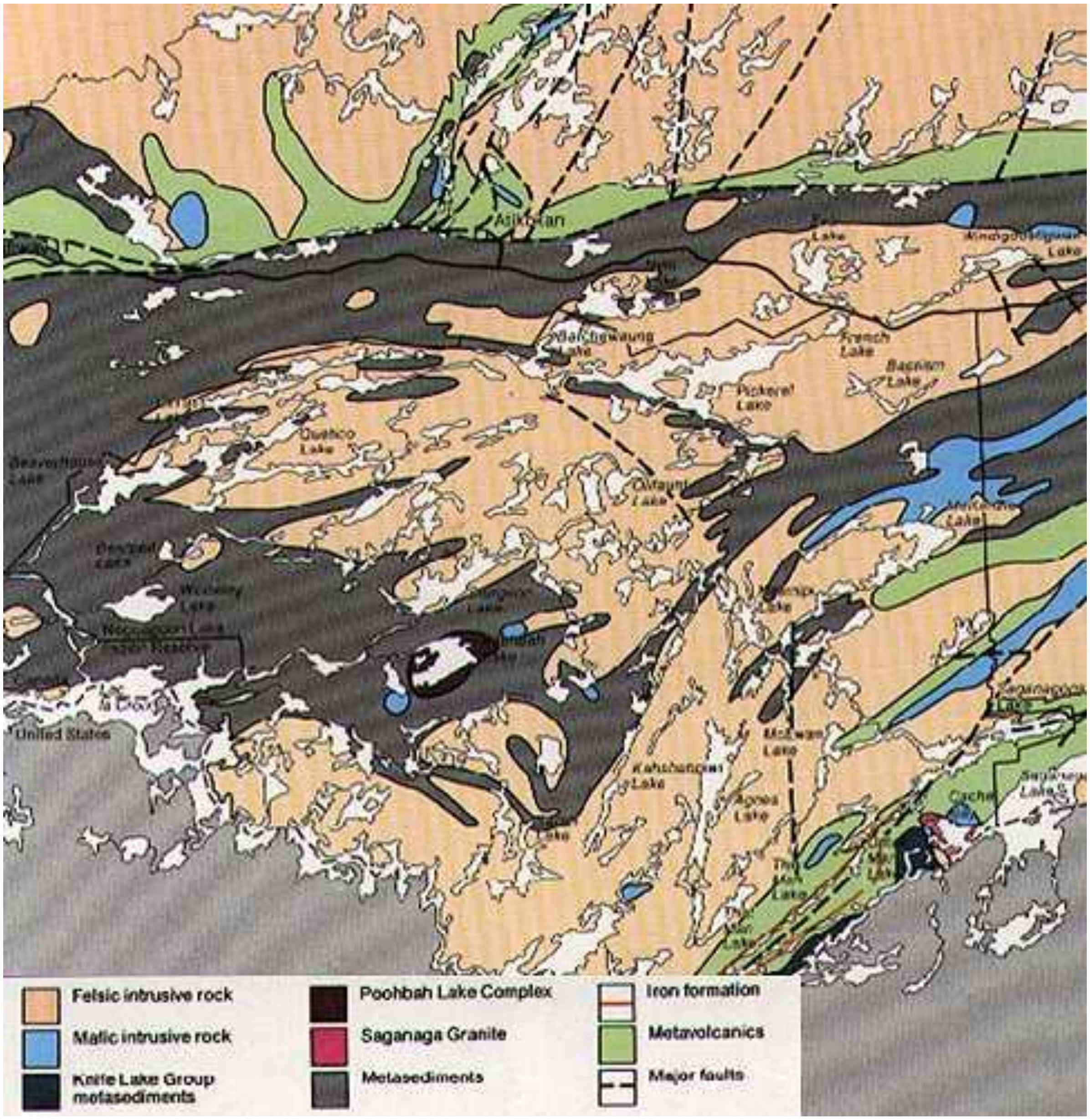

Figure 3.2 Geology of Quetico Provincial Park. Source: The Quetico Foundation, 2007.

3.2.2 Climate

In the Quetico-Superior Ecotone, the primary influence on large-scale structure is the confluence of three major air streams: tropical, arctic and pacific (Kronberg, Watt &

Polischuk, 1998). The winters consist of long periods of clear, dry and cold arctic-air-mass weather, mingled with shorter periods of cloudy, warmer and snowy weather. Large winter storms are typical, pushing the temperatures to -40ºC (Heinselman, 1996). The summers are a mix of some hot and humid days, as a result of Gulf air masses, with more frequent clear, dry and cool arctic air periods. High temperatures of 27ºC occur frequently in July and August, occasionally reaching a maximum of 34ºC (Heinselman, 1996). The fall freeze up generally begins in late October, with a spring break-up beginning between mid-April and late May (Heinselman, 1996), although the shoulder seasons in boreal forests are extending due to global climate change (Stocks et al., 1998; Wotton & Flannigan, 1993). The annual total precipitation (rain plus snowfall water equivalent) is approximately 70 cm for this region, with 40% falling in June and August, enhancing the summer forest growth (Heinselman, 1996; OMNR, 1977). The average annual snow fall in the region ranges from 140-180 cm, with the first snow fall beginning in late October and the last between the of April to early May, with nearly continuous snow cover until mid-April (Heinselman, 1996).

Fire season is officially from April 1 until October 31st each year. These dates are based on the seasonality of fire activity. During this time, the prevailing winds at the Atikokan Environment Canada weather station are south to northwesterly ranging from 6.8 to 8.5 km/hr (Environment Canada, 2007). Typically spring fires occur in boreal forests after snowmelt, and prior to deciduous green-up, as the needles of coniferous tree species are very dry until growth begins and due to the abundance of dry dead fuels from the previous season (Heinselman, 1996). Of particular concern are those fires that occur during the foliar moisture dip, a short event that occurs prior to green-up characterized by a substantial decrease in live fuel moisture. During the spring, ignitions are more likely to be human-caused, whereas lightning is more common from June to August (Heinselman, 1996). Thunderstorms accompanied by sufficient precipitation will extinguish most ignitions. Dry lightning during drought periods in the late summer have potential to cause large fires (Heinselman, 1996). Summer fires require longer periods of drought to dry out fuels and soils, as from mid-June to August the growing understorey and the deciduous forest component is moist and succulent (Heinselman, 1996). By mid-August the dominant canopy species are going dormant and grasses begin curing, causing an increased fire hazard, particularly in combination with drought conditions. With drought conditions, this hazard remains until approximately the beginning of October when the daily burning period is shortened (Heinselman, 1996).

3.2.3 Forest Stands

Quetico Provincial Park is part of the Quetico-Superior Ecotone, located in Northwestern Ontario and Northern Minnesota (48-50ºN, 89-90ºW), which is a regional-scale ecotone between three major vegetation biomes (boreal forest, northern temperate forest, and prairie) (Kronberg et al.). The forests have an east-west transition within the boreal biome from moist to dry forests (Kronberg et al., 1998).

Forests in Quetico are mainly composed of mosaic of early successional and full successional, even and broadly-aged stands (Woods & Day, 1977). The majority of the forests are dominated by Pinus banksiana (jack pine), Picea mariana (black spruce), Populus balsamifera (poplar), Betula papyrifera (white birch), Pinus resinosa (red pine) and Pinus strobes (white pine), originating from large wildfires that occurred in the late 1880’s and early 1900’s (Kronberg et al., 1998; Rowe, 1972; Woods & Day, 1977).

Jack pine is considered the most abundant forest community within Quetico Provincial Park, dominating over 30% of forests and commonly associated with poplar and black spruce. Black spruce is the second most abundant community group, dominating over 26% of the forests. Approximately 20% of forests in Quetico are dominated by poplar, though it occurs in 70% of the forests as the dominant, secondary or tertiary species. White birch dominates approximately 10% of the forests, commonly found with poplar and black spruce. Red pine is dominant in less than 5% of the forests, and commonly associated with white pine, which dominates only 3% of the forests, but occurs as a secondary species in approximately 13% of the forests. Balsam Fir can be found in approximately 16% of the forests, but only dominates in 3% (Woods & Day, 1977).

3.2.4 Fire Regimes

Historical fire regimes are thought to be similar between Quetico Provincial Park and Boundary Waters Canoe Area Wilderness (BWCAW), located adjacent to the park in the United States (Heinselman, 1996). In BWCAW the fire cycle was approximately every 122 years in the Pre-settlement era (Heinselman, 1996). This era can be characterized as the period of early arrival of European settlers, when a regional increase of fire as a resulted due to an increase in accidental human-caused ignitions, but was coupled with greater suppression capabilities (Conard et al., 2001; Heinselman, 1996). The fire cycle in the BWCAW was approximately every 87 to 100 years during the settlement period as fire suppression became more effective (Heinselman, 1996; Kronberg et al., 1998). From 1911-1972, fire suppression capability increased, expanding the average fire cycle to an 800-2000 years (Heinselman, 1996; Kronberg et all, 1998). This equates to natural forest stands being replaced by balsam fir and hardwood shrubs, and humus accumulations to the point of impeding nutrient cycling (Van Wagner, 1978; Woods & Day, 1975).

The historical fire regime varied significantly throughout Quetico Provincial Park, depending on the forest stand type, e.g. Jack Pine burns approximately every 80-150 years while White Pine burns every 180-250 years (Woods & Day, 1977). In pre-suppression times, approximately 4,850 hectares would have burnt annually on average in Quetico Provincial Park (Woods & Day, 1977).

Quetico Provincial Park followed the common pattern of fire management in Ontario. In 1917, the Forest Fire Prevention Act was passed. The forest fire prevention system continued to expand, including the use of lookout towers, ranger stations and supply warehouses for fire fighting equipment (Li, 2000). By 1960's fire suppression had become effective at reducing the number fires on the landscape through increasing effectiveness of detection and success of initial attack tactics. The mean interval between fires prior to effective fire suppression was 78 years (Woods & Day, 1977). The nearby Lake of the Clouds had a mean return interval of 66 years for the last 1000 years. However, there is an increase in fire frequency from 1930-39, when drought conditions persisted and more fires escaped control. In 1977, the statistics are drastically different, with a mean fire return interval of 870 years. If we examine the percentage of area burned, we see that over 75% of 93,078 ha burnt between 1860-1919. From 1920-1939 17% burned, and only 4% burnt

1940-1977, which accounts for the maturing forest stands (Woods & Day, 1977). In order to achieve pre-suppression fire return intervals, approximately 12,000 ha would need to be burned within each 93,000 ha area every 10 years, equating to 4856 ha/year (Woods & Day, 1977). With a change in fire management policy in Ontario parks that allows wildfires in extensive fire zones and supports the use of prescribed burns, the fire return interval has decreased. However, the fire return interval has not returned to pre-fire suppression levels. For a thorough review of recent changes to the park's fire management policy, see OMNR (2002) and OMNR (1993).

Chapter 4
Methodology

Using a fire growth simulation model I tested whether changing highly flammable fuels to less flammable fuels reduces the overall landscape flammability. A reduction in flammability would help to protect important values at risk such as communities and timber resources. I used a deterministic fire growth simulation model to determine if random fragmentation of highly flammable fuels decreases average area burned under extreme fire behaviour conditions. Fire growth models are data intensive. The quality of data is critical to the creation of quality outputs from the model. For an overview of data used for this research see Figure 4.1.

Minimal required data for Prometheus and Pandora are:

- Fuel type grid in grid ASCII format, based on FBP fuel types
- Projection data indicating the projection information that each input file was created in (projection must be identical for all inputs) in an ASCII text file
- FBP fuel lookup table that defines ASCII grid numbers as fuel types, and display properties
- Weather data in ASCII text file
- Fire ignition data in generate ASCII or shape file format

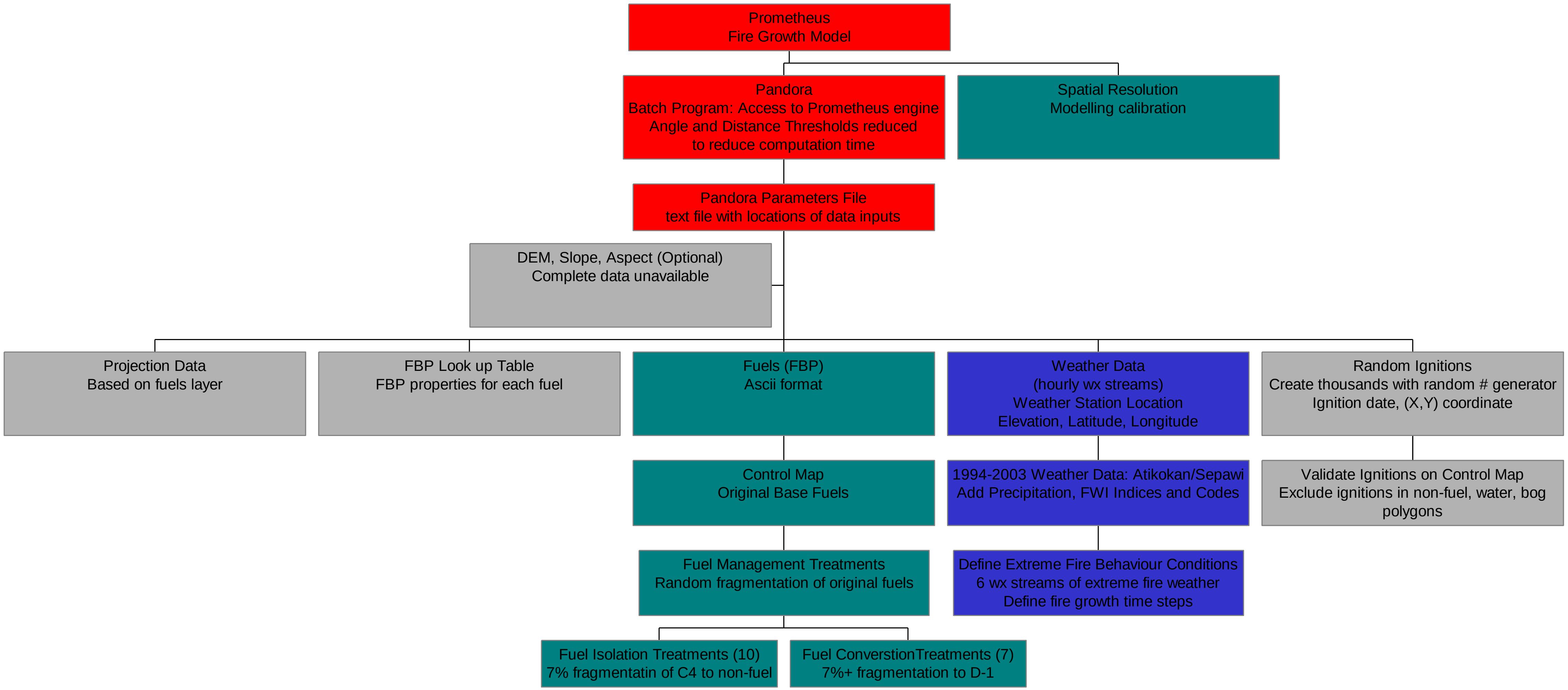

Figure 4.1 Fire Growth Modelling Methodology detailed flow chart.

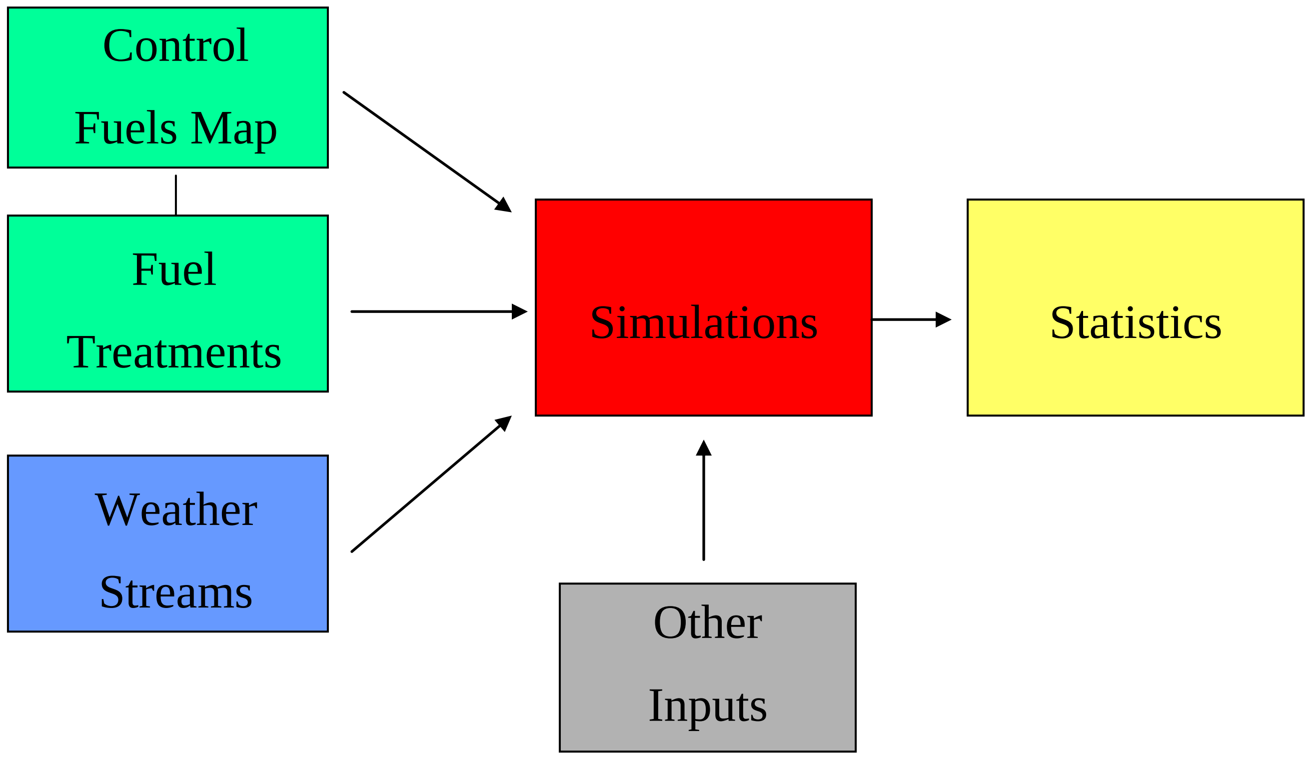

Figure 4.2 Major Thesis Methodology Components: This flow chart depicts the main components used to perform this research. Each main area is described in more depth through Section 4.0, in addition to a detailed flow chart (Figure 4.1).

4.1 Control Fuels Map Creation

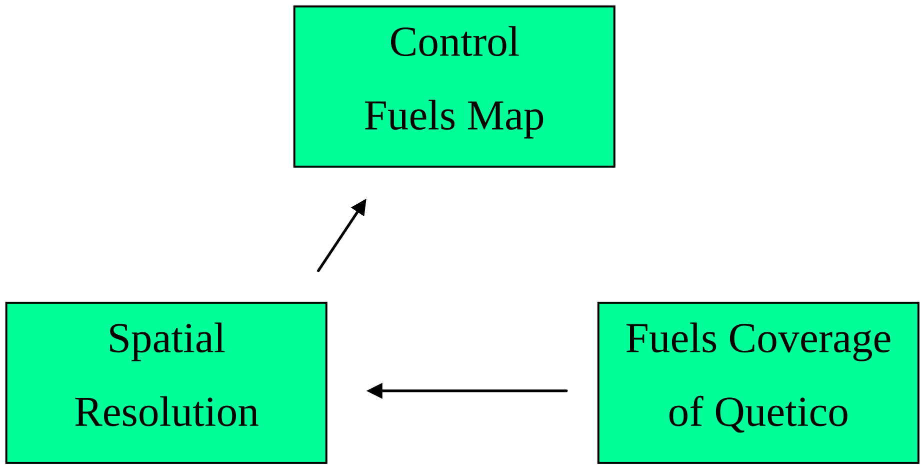

Figure 4.3 Control Fuels Map Flow Chart: Fuels coverage from Quetico Provincial Park and a buffer area, based on a chosen spatial resolution, was used to create the Control Fuels Map.

J. Caputo of the Ontario Ministry of Natural Resources provided fuel maps of Quetico Provincial Park. The fuels coverage data was based on 1996 Landsat image data, classified together Forest Resource Inventory (FRI) data layers in order to convert vegetation data to FBP fuel types. This map did not include those polygons that have been affected by spruce budworm infestations. These patches, and other polygons with missing data, were interpolated using fuels data from Landsat images with vegetation classifications. The 1995 Fire 141, which burned 25,000 ha during high fire danger conditions, was reclassified as a slash fuel type. A. Grant, a fellow University of Waterloo Graduate Student, conducted the interpolation and we worked collectively as team to gather Quetico Provincial Park data necessary for Prometheus simulations.

4.1.1 Spatial Resolution

Prometheus, and by extension Pandora, can use any spatial resolution. While a finer resolution typically yields more detailed fire growth, the user is advised to use a resolution commensurate with the resolution of the input data. Geospatial landscapes for this research are divided into cells, or pixels. Spatial resolution refers to the size of each pixel in the landscape. I used a spatial resolution of 50m, because it was coarser than the original fuels resolution of 30 m, and significant linear features such as rivers continue to act as unbroken natural firebreaks. It is important to use a resolution that is at least as coarse as the original input data in order to avoid over interpolating and thus degrading the quality of modelling data. As well the computation time becomes onerous when thousands of iterations are necessary.

Spatial extent was defined as a large subset of the central and north-eastern portion of Quetico Provincial Park and a buffer zone along the park boundaries, which allowed the model to grow large landscape level fires. In caution one should note that this choice slowed down the modelling and used over 1GB RAM. The fuels coverage used for this research was approximately 5542 km^2, which included the subset of Quetico Provincial Park and buffer zone to the north and east of the park. This total included cells with no available data on the perimeter of the landscape. After removing the area of these cells, the size of the landscape is 4742 km^2. The CWFGM Project Steering Committee (2006) suggested that size of the fuel file should be 300-400 rows and 800-1200 columns. The fuel file used in this research was 1811 rows and 1224 columns. This helped to determine if a larger landscape scale approach could be modelled using Prometheus. Again, I caution that this slows processing speed and requires more RAM.

4.1.2 Fuels coverage of Quetico Provincial Park

As Prometheus requires raster format, I used a simple toolbox command in ArcGIS 9.0 to convert the fuels coverage from vector to raster format, with a specified 50 m resolution. The fuels coverage was then exported in ASCII format. The final step was to find and replace redundant fuel types based on the standard Prometheus Look-up Table, while in grid ASCII format. For example gravel/roads were reclassified to non-fuel.

Using a subset of Quetico Provincial Park as a realistic fuel mosaic (Figure 4.3), my research focuses on the conceptual basis for random fuel management, not a prescriptive fuel management strategy for this park. Therefore extensive ground truthing of the fuels coverage was not necessary.

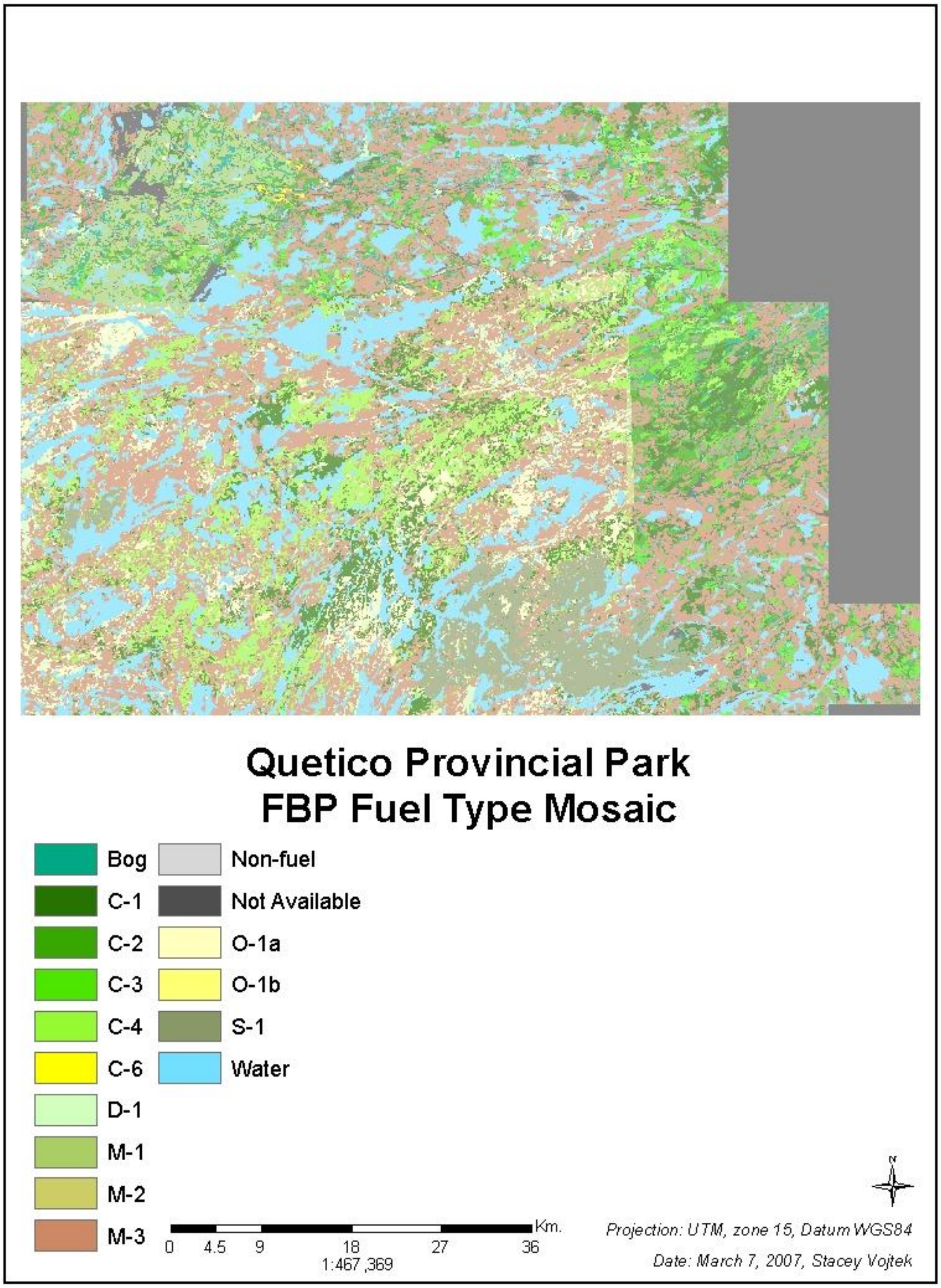

Figure 4.4 FBP Fuel Mosaic: Subsection of Quetico Provincial Park and buffer zone.

4.2 Random Fuel Treatments

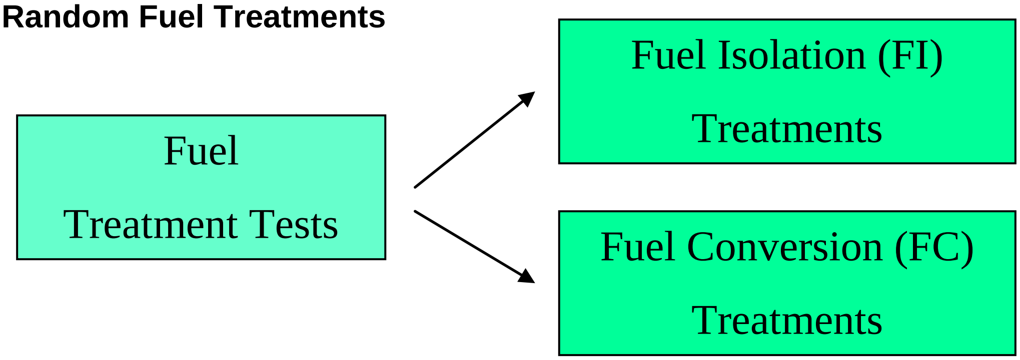

Figure 4.5 Using ArcView 3.3, the Control Fuels Map was used to create fuel treatments tests. Based on general observations from these tests, fuel isolation and fuel conversion treatments were created.

Sample fuel treatment maps were created to test the minimum percentage fuel fragmentation needed to achieve at least a 50% reduction in wildfire size. C-4 (Immature Jack or Lodgepole Pine) was chosen as the target fuel as it is a highly flammable fuel type found in southern continental boreal forests. Though there are other flammable fuel types, such as S1 (Slash) or C-2 (Boreal Spruce), C-4 is found throughout most of Quetico Provincial Park. S1 and C-2 are not found consistently throughout the park. As well, C-4 reaches its equilibrium rate of spread quickly in comparison to other conifer fuels under extreme fire behaviour conditions.

Fuel treatments were created using the Spatial Analyst extension in ArcView 3.3. Within the control map's attributes table, I created three new attribute fields: square kilometres (built-in ArcView 3.3 function), a field of random numbers from 1-100 (using ArcView 3.3 Field Calculator), and a treatment field with the same FBP fuel values as the control map fuels field. Using the query function, I selected all C-4 (Immature Jack or

Lodgepole Pine) fuel polygons within the treatment field. From within this selected set, using random numbers and square kilometres fields, I queried polygons to select the desired percent of area fragmentation (e.g. 1.2% of the total area). These queried polygons were changed from C-4 to non-fuel. This treatment map could then be added to the ArView 3.3 file as a shape file (vector) and exported as a grid ASCII to be used by Prometheus and Pandora.

The test fuel treatment treatments consisted of 1.2%, 1.8%, 2.3%, 3.0%, 3.5%, 4.1%, 4.7%, 5.2%, 5.8%, 6.4%, 7.0%, 7.6%, 8.2%, and 8.8% of the total landscape area altered from C-4 to non-fuel. These increases were based on incrementally adding polygons to the treated area. A maximum of 8.8% was fragmented as C-4 fuel type composes 8.8% of the total landscape. Non-fuel was chosen as a fuel isolation (fragmentation) treatment, with the assumption that a fuel treatment prescription would be effective at eliminating fire spread, representing a change to water, open gravel or bedrock.

Running thousands of iterations for each fuel treatment is a time consuming process, particularly for simulating fires in extreme weather conditions. Therefore I chose to determine a minimum % fragmentation needed to achieve a 50% reduction in area burned, thereby eliminating less effective fragmentation treatments. Through simple linear regression of the test treatment results, I determined a minimum fuel treatment needed to begin rigorous testing of fuel treatments.

Using ArcView 3.3, the fuels coverage maps were used, in vector format to create fuel treatment maps. Fuel composition of the Control Fuels Map (in vector format) was repeatedly fragmented to create ten fuel treatments. This was achieved by converting a percentage of the randomly chosen polygons from Immature Jack Pine to non-fuel. This equates to partial and complete conversion of Immature Jack Pine stands, depending on the size of polygon converted. See Figure 4.5 for a sample treated landscape.

4.2.1 Fuel Isolation (FI) Treatments

I created 10 new fuel treatments using the same methods used to create the test treatments. I randomly treated 7% (approximately 332.6 km^2) of the C-4 in the original fuel map, converting it to non-fuel. Multiple fuel isolation treatments with the same percent treated area was necessary to ensure the pattern of fragmentation was not the critical variable being tested, but rather the percentage of fragmentation that was significant to the end results (area burned).

4.2.2 Fuel Conversion (FC) Treatments

In addition to fuel isolation treatments, I tested fuel conversion treatments. Through conversations with fire managers in Canada, interest has been expressed in developing a greater understanding of fuel conversion as a tool to limit the extent of wildfires. In order to simulate fuel conversion on the landscape, highly flammable fuels must be converted to less flammable fuels, such as the deciduous D-1 (Leafless aspen) fuel type. Seven fuel conversion treatments were created using similar methods as the fuel isolation treatments, with following differences:

1. D-1 (Leafless aspen) was used as the fuel-conversion type instead of non-fuel for all seven scenarios.

2. A greater percentage of fuels were converted to reduce wildfire size as fuel conversion is less effective at reducing area burned than conversion to non-fuel (isolation); therefore other source flammable fuels were converted to obtain a larger percentage of total area conversion.

For specific fuel conversions see Table 4.1.

Table 4.1 Fuel conversion configurations for Treatments 11 to 17.

Treatment #	%	Original Fuel Type	New Fuel Type
11	7	C-4	D-1
12	8.8	C-4	D-1
13	17.1	C-4, C-1	D-1
14	21.9	C-4,C-1,C-2	D-1
15	25.2	C-4,C-1,C-2,C-3	D-1
16	38.2	C-1, C-2, C-3, C-4, M-3	D-1
17	13.0	M-3	D-1

Table 4.2 FBP Abbreviations and Descriptions

FBP Fuel Type	FBP Fuel Type Description
C-1	Spruce-lichen Woodland
C-2	Boreal Spruce
C-3	Mature Jack or Lodgepole Pine
C-4	Immature Jack or Lodgepole pine
M-3	Dead Balsam Fir Mixedwood,
D-1	Leafless Aspen

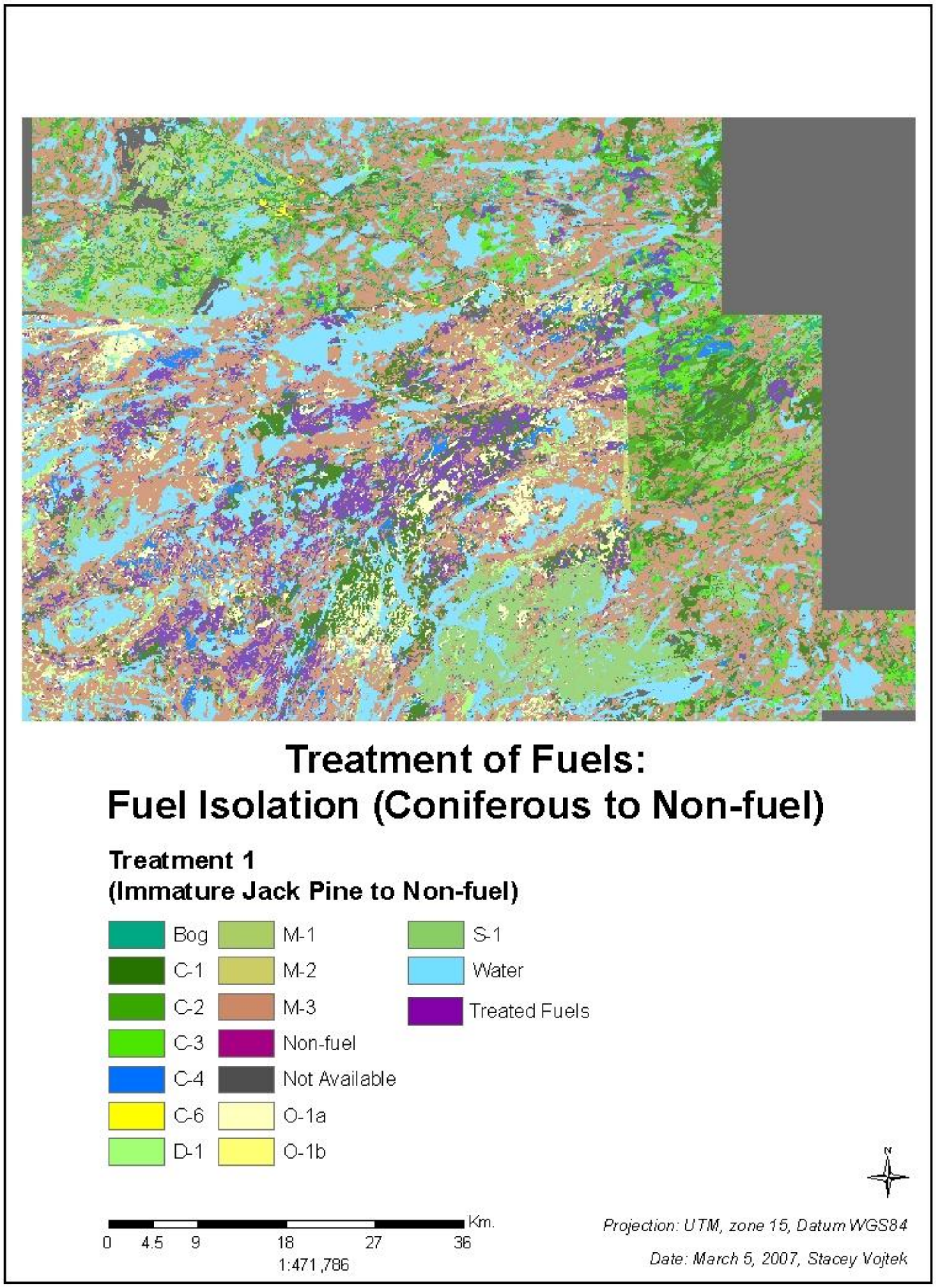

Figure 4.6 Treated Fuels Map highlighting Fuel Isolation Treatment 1.

4.3 Fire Weather Stream Creation

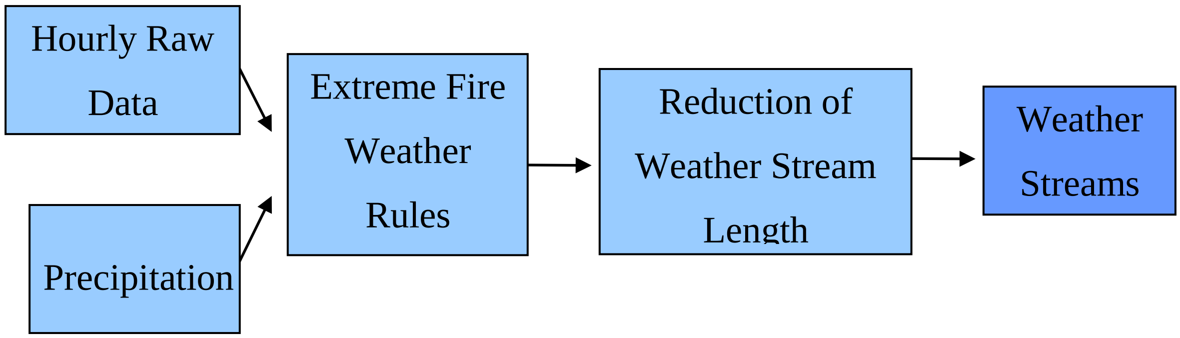

Figure 4.7 Weather Streams Flow Chart: Fire Weather Streams were created through combining hourly weather data with daily precipitation data. Extreme Fire Weather Rules were applied to this new dataset to determine periods of extreme fire behaviour weather, producing 14 weather streams. The weather streams were reduced in length further by deleting periods of no and low fire growth potential. Of the 14 weather streams, 6 were chosen for use in this research.

Finney (2001) found that to reduce fire behaviour the fuel treatments should target fires burning under specific weather and fuel moisture conditions. As fire intensity and size are increasing due to more extreme weather and fuel conditions, it is relevant to model fuel treatments under extreme fire weather conditions.

Fire Weather data was provided by J. Caputo with Ontario Ministry of Natural Resources (OMNR) and by B. Mills with Environment Canada. These two datasets were from the Atikokan OMNR weather station, which provided daily weather data from 1981-1995, and the Atikokan Environment Canada weather station, which provided an hourly weather data set from 1994-2003. This raw weather data were analyzed, reduced in length to represent the extreme weather conditions that were desired for this research and formatted to

Prometheus specifications. The creation of weather streams required several steps, as follows.

4.3.1 Precipitation

Hourly weather data are preferable to daily weather as they capture a more realistic range of daily weather trends and how weather influences the fire environment on an hourly basis, affecting the overall fire growth. Precipitation was available daily; therefore daily precipitation values were placed in the hourly weather data files. How to apportion the precipitation by hour presented a new dilemma, as placing all the precipitation data in one hour would not usually represent realistic precipitation patterns.

The following rules were created to be consistent and in an attempt to mimic how precipitation would occur in reality.

1. Daily precipitation was apportioned evenly in all hours that had > 95% relative humidity, between the hours of 8am of the previous day to 7 am of the current day.
2. If none of the hours from 8 am the previous day to 7 am of the current day had >95% RH, the full amount of rain was inserted in the hour with the highest relative humidity value.

Using SAS (originally called Statistical Analysis System) software, B.M. Wotton created a program to systematically place the precipitation data according to these placement rules.   The SAS program was called “Read EC daily wx format.sas”.

4.3.2 Extreme Fire Behaviour Weather Streams

Fire indices and codes are needed to define extreme weather streams from within a larger data set. However a continuous daily weather dataset is required to calculate the FWI codes and indices. The daily weather data set from the OMNR was discontinuous. To fill in 68 missing dates, data from the temporary daily Environment Canada Atikokan (20700) and the Sepawi (20713) weather stations was used. These missing days were documented, as hourly weather streams containing these dates would not be used for modelling purposes in order to maintain data source consistency.

The SAS program FWI.SAS, developed by B.M. Wotton, was used to calculate the FFMC, DMC, DC, ISI, BUI, and FWI for daily weather, using start-up FWI values from the OMNR Atikokan weather station. The SAS program uses equations developed by Van Wagner (1987) and follows the Fortran calculation program as described by Van Wagner and Pickett (1985). This SAS program used the continuous weather streams, as outlined previously, to produce a file with the FWI codes and indices from which to choose extreme fire weather.

Extreme Fire Weather Rules

From within the SAS output file with FWI codes and indices, weather stream dates were chosen with the following rules:

- Start Date: Initial Spread Index (ISI) of >10.0 sustained for 2 days, AND 0.0 mm precipitation on the first day the ISI > 10.0
- End Date: ISI of <2.2 sustained for 2 days AND precipitation of >5 mm

These rules were based on fire indices and codes from Table 4.3 and applied to the daily weather data set to determine the start and end dates for extreme weather streams. Only weather streams without data gaps were chosen (no missing days and minimal hourly gaps). This resulted in 14 weather streams of various lengths, approximately representing the 90th percentile of typical weather in this region.

Table 4.3 Ontario Ministry of Natural Resources Fire Weather Index Fire Class. Source: J. Antoszek, Dryden OMNR (2005).

ONTARIO FIRE WEATHER INDEX SYSTEM CATEGORIZATION								
FWI CLASS	FWI COMPONENTS							
	FFMC	DMC	DC	ISI	BUI	FWI	DAYS	FIRES
LOW	0~80	0~15	0~140	0~2.2	0~20	0~3	58%	20%
MODERATE	81~86	16~30	141~240	2.3~5.0	21~36	4~10	27%	32%
HIGH	87~90	31~50	241~340	5.1~10.0	37~60	11~22	13%	33%
EXTREME	91+	51+	341+	10.0+	61+	23+	2%	15%

4.3.3 Reduction of Weather Stream length

As noted, the weather streams were shortened. This was done for two reasons: 1) When using real weather data, fire growth models tend to over predict the size of fires with low fire behaviour, therefore fire growth time steps (hours) had to be further refined; and 2) When long weather streams are used in Prometheus, simulations can each take upwards of more than 24 hours. Processing long weather streams often surpasses computer memory and therefore simulations abort before all time steps are completed.

A decision was made to further refine the definition of a fire growth period. The elimination of no to low growth fire periods was essential to reduce the length of weather streams. To do this, an hourly weather stream containing FFMC, DMC and DC was needed in order to apply further refined fire growth period rules. A program named HFFMC.C was used to calculate FFMC values for the hourly weather data set (1994-2003). This program is based on the Van Wagner (1977) methodology for calculating hourly FFMC. DMC and DC values were manually added from the daily weather stream to the 14 weather stream files.

Using rules based on general fire behaviour knowledge, I shortened the weather streams by eliminating time steps of low spread potential. The elimination of these time steps decreased the problem of over prediction common to fire spread models. The decision to use relative humidity and FFMC thresholds was based on the rationale that operational fire management recognizes minimal fire growth results in hours with an FFMC below 80 or an RH above 60% results. R. Quenneville, a National Duty Officer and fire behaviour analyst with Parks Canada, agreed that when combined with ISI threshold values, these additional thresholds are conservative indicators of very low fire growth in the field (R. Quenneville, Pers.Comm, 2006). In fire behaviour prediction scenarios, he and his colleagues created a set of rules to determine times of no fire spread. These rules are as follows:

Weather time steps will be deleted if:

- Relative Humidity of > 40 %, or
- Turn off the fire between 21:00 and 11:00, or
- Precipitation > 2mm, or
- FFMC < 85

Based on Table 4.3, I chose a more conservative FFMC value of < 80, as this table was created for the Dryden Fire Management Region, encompassing Quetico Provincial Park. In addition, these added thresholds reduced fire growth computation time from 48+ hours to approximately one hour. In early 1996, when I ran the fire iterations, Pandora was not capable of turning the fire off and on based on time of day. The decision to eliminate hours below an FFMC of 80 is supported by one finding of Beck and Armitage (2004). They found that Van Wagner's hourly FFMC model does not accurately estimate the moisture content of feathermoss and jack pine needles within the lower FFMC ranges, with the differences decreasing and becoming small with an FFMC greater than 77.

As determined by rigorous literature review and through consultation with field experts across the country, I determined that the literature does not adequately address this fire growth methodology issue. Therefore the methods to determine realistic fire growth time steps are in its infancy and require further research. As there is no consensus on appropriate FWI codes or indices and values to use, I chose weather values based on operational fire management knowledge and through consultation with Canadian fire experts.

A code line in Microsoft Excel was used to determine the time steps with a relative humidity greater than 60% or an FFMC below 80. These time steps were manually deleted from the hourly weather streams for the 14 weather streams, ensuring to keep a continuous hourly weather stream that Prometheus requires.

The formula used was:

```
=IF(OR(D2>60,H2<80),"YES","NO")
```

D2: represented the column with % relative humidity values

H2: represented the column with FFMC values

With the identified dates from the ISI and precipitation criteria, the 14 weather streams were extracted from the newly revised weather data set.

Once the 14 weather streams were extracted from the hourly weather data set, I chose 6 weather streams of the 14 that represented a variety of weather stream lengths, as the number of time steps affects the final area burned. This step has allowed for a larger number of ignition iterations, thus increasing the statistical rigour.

4.4 Other Inputs for Fire Growth Simulation Modelling

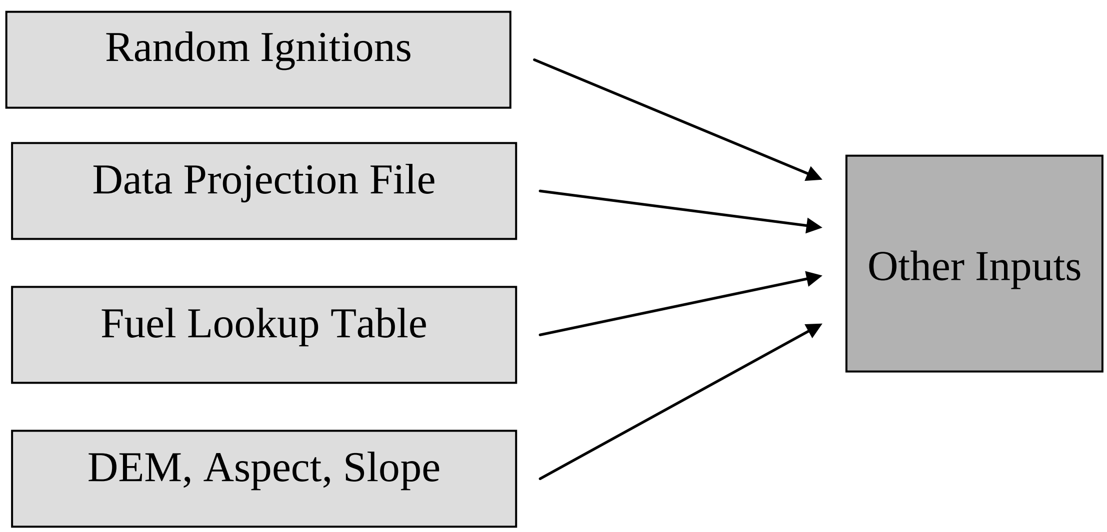

Figure 4.8 Other Inputs Flow Chart: Additional inputs are needed in order to the fire growth simulation model, Prometheus, and it's associated batch simulation program, Pandora. These inputs are described in detail in sub sections 4.4.1, 4.4.2, 4.4.3, 4.4.4.

4.4.1 Random Ignitions

30,000 random ignition coordinates (X, Y) were created using a random number generator in Microsoft Excel. B.M. Wotton created a program called FindWater.exe to eliminate all ignitions that landed within water, bogs and non-fuel. From this paired-down number of ignitions, each of the six weather streams were assigned 275 random ignitions that would be run on each fuel treatments, for a total of 1650 unique ignitions, on 17 fuel treatments and the control fuels map. Of the 275 ignition coordinates, approximately 75 were eliminated due to a malfunction in the Prometheus program. The error occurred when an ignition coordinate was located on the borders of two fuel polygons, of which one polygon was a non-fuel. The removal of this source of error was justifiable as the error was related to a geographic problem in the software, and was not an indication that fire growth would not occur in those locations. This left approximately 200 ignitions that successfully ignited a fire for each weather stream, for each fuel treatment and control fuels map.

4.4.2 Data Projection File

A data projection file is necessary when using Pandora in order to import grid and vector data into the project. This file tells Prometheus the projection and geospatial datum used to create the geographic coverage, and is used by Prometheus to display all the data in the same projection. Data were projected in UTM 15, with World Geodetic System 1984 (WGS84) datum. WGS84 is the current reference system used by the Global Positioning System. It is geocentric and globally consistent within ±1 m. The CWFGM Project Steering Committee (2006) recommends using the North American Datum of 1983 for Prometheus, as this local datum (=provides a frame of reference to a local point of origin) is best suited for the earth's surface in North America. The Quetico Provincial Park data were created using the geocentric datum WGS84 (=provides a frame of reference to the centre of the earth), which can support geographic location measurements worldwide.

4.4.3 Fuel Look-up Table

Prometheus requires a Fuel Look-up Table (.lut) to read grid ASCII fuel maps. A standard Prometheus LUT is available through a sample dataset on the website (Anonymous, 2007). An updated version of this LUT containing Quetico specific fuel type numbers was used for this research.

4.4.4 DEM, Slope and Aspect

At the time of fire growth modelling (December 2005-January 2006) the Digital Elevation Model (DEM) for Quetico Provincial Park was incomplete. Prometheus and Pandora cannot use a DEM if there are gaps in the data coverage. A new DEM version was not completed within the timeline of this research. Through consultation with B.M. Wotton of the Canadian Forest Service and the University of Toronto, I decided that because Quetico Provincial Park has relatively flat terrain, there would not be a significant elevation effect on fire behaviour. Fuel type differences as a result of elevation changes would likely account for elevation differences; particularly in comparison to the Canadian Mountain ranges where elevation has a drastic effect on fire behaviour and in a fire growth modelling environment. Though it would have been preferential to use all possible data inputs, the timeline of a completed DEM was unknown. Therefore the decision was made to not use the DEM, slope and aspect.

4.5 Pandora Batch Simulations

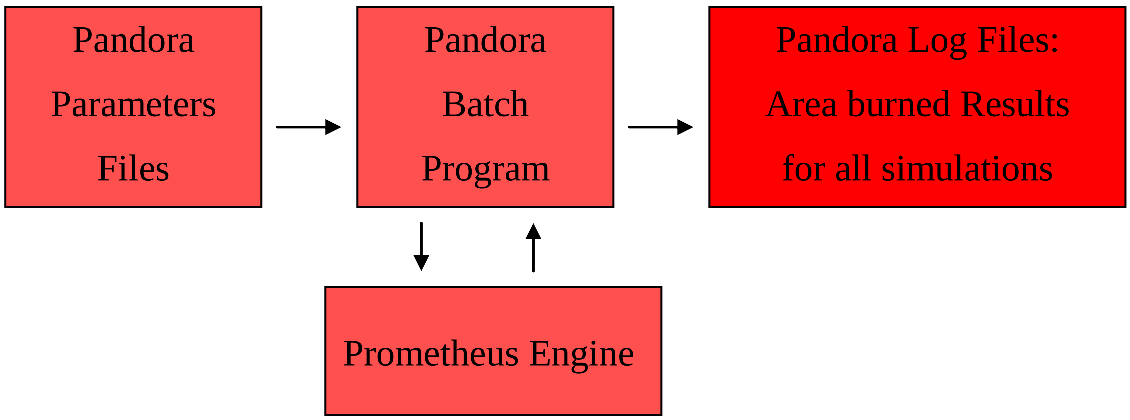

Figure 4.9 Simulations Flow Chart: To use the Pandora Batch Program, each series of simulations requires a Pandora Parameters File. This file identifies the location of the input data. Pandora accesses the Prometheus engine in order to simulate the fires according to specifications in the Pandora parameters files. This information is relayed back to Pandora to create a .log file with area burned in hectares for each simulation.

Pandora was executed using parameters files that represented all unique combinations of the control fuels map or one of the 17 treatment maps, 1 of 6 weather streams representing realistic fire growth under fire behaviour conditions, and 1200 unique ignition coordinates. With over 20,000 simulations at approximately 1-2 hours per simulation, computation time needed to be reduced further. Reducing the angle threshold from 171.89 to 5, and increasing the distance threshold from 1 to 2 reduced computation time from several hours to a few minutes. Through discussion with the Prometheus engine programmer, I determined that this adjustment in distance and angle thresholds is not a concern for resulting data quality for area burned. These components of Prometheus are essentially smoothing factors for the ellipse calculations to represent more representative fire shape at a small scale. This feature is unique to the Prometheus fire growth engine, as FARSITE, the American fire growth simulation model, does not use angle or distance thresholds. This adjustment was applied to all fire simulations, thus the reduction in area burned as a result of fuel treatments was not affected by this adjustment.

After executing all Pandora parameter files, each containing 275 ignition coordinates, area burned for each ignition was stored within a LOG file. The area burned was extracted for each ignition and tabled in an excel spreadsheet categorized by weather stream and fuel treatment scenario.

4.5.1 Pandora Parameters File

Pandora requires a "parameters" file to direct the program to locate the input files and to access the Prometheus engine (Appendix B). The user indicates the total number of iterations, weather station location data, number of hours in the hourly weather input file, initial FFMC, DMC, DC and hour data in the weather file, the method of calculating the FFMC, the percentage of cured grass, the ignition date and location, the angle and distance thresholds for calculating the fire perimeter, the time interval to calculate the fire perimeter, and the output requirements. When Pandora was first developed, some difficulty arose with the fire perimeter shapefile output function of Pandora. Therefore, for this research, I used a batch log file with final area burned for each ignition.

4.6 Statistical Analysis

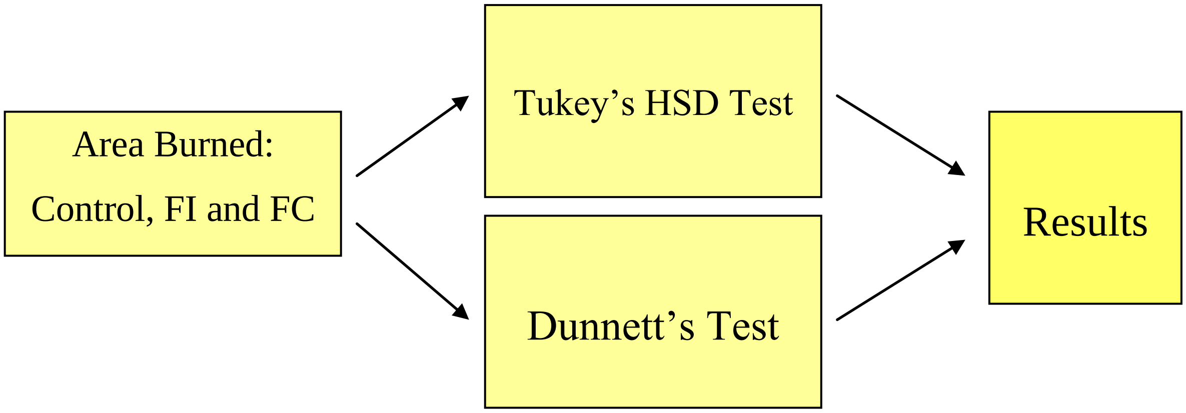

Figure 4.10 Statistics Flow Chart: Tukey's HSD and Dunnett's tests were used to analyze the differences between the area burned of the treatments from the control fuels map.

The statistical analysis was designed in cooperation with E. Harvey, a statistician from the University of Waterloo. I used two post hoc multiple comparison tests - Dunnett's, and Tukey's Honestly Significant Difference (HSD) - to compare average area burned results between a control fuels map and the 17 fuel treatments. Tukey's analysis performs all possible comparisons between every treatment. It controls for Type 1 experiment-wise error rate, which was held at 5%. Type 1 errors (false positive) occur when the null hypothesis (there is no effect) is incorrectly rejected (i.e. null hypothesis is true). Type II (false negative) errors occur when a false null hypothesis is not rejected (i.e. the alternative to the null hypothesis is true). Dunnett's test compares all treatments only to the control, i.e. the base map of original fuels (no fuel treatment). In order to analyze all ignitions together and determine if characteristics of each weather stream were influencing the results, the results were blocked prior to the experiment (i.e. the treatments were matched by weather stream).

This was done to remove variation between the weather streams and then tested for the statistical differences between fuel treatments. Variations associated with the block (the main effect and interaction) are isolated in the randomized block statistical analysis (Zolman, 1993). If blocking were not used when analyzing all weather streams together, the sources of variance between the weather streams would contribute to the error variance (Zolman, 1993).

The Tukey HSD test was used in addition to the Dunnett's test as it gives reasonably accurate results if sample sizes are nearly equal (Zolman, 1993). This sample sizes were the same within each weather stream, however they differed slightly between weather streams. As well, the Tukey HSD allowed for testing between treatments to test whether the pattern of fuel treatment was significant, opposed to the percentage of fuel treatment as the main factor in reduction of average area burned. Dunnett's is an appropriate test because the likelihood of making Type 1 errors increasing as the number of post hoc comparisons increases, and Dunnett's is a specialized comparison technique for familywise (FW) error rate that is designed to compensate for the increased number of Type 1 errors.

Chapter 5
Results

Seventeen treatment scenarios were created to test two concepts: fuel isolation and fuel conversion. The ten fuel isolation treatments consisted of converting 7% of Immature Jack Pine to non-fuel. The seven fuel conversion treatments consisted of incremental % of flammable fuels being converted to Leafless Aspen. See Table 4.1 for fuel conversion configurations. Fuel isolation and fuel conversion will be referred to as FI and FC respectively.

A total of 28,050 ignitions coordinates were run in Pandora, resulting in 21,352 successful fire simulations, after accounting for the ignition error as described previously. The area burned for each ignition was organized by weather stream, then by treatment scenario. For an analysis of all the weather stream ignitions together, the data were organized by treatment scenario only.

Area burned summary statistics by weather stream and blocked analyses are listed in Table 5.1. Using Tukey's HSD and Dunnett's tests, overall there were considerable decreases in area burned between the control fuels map and the treatments. All FI treatments were effective at reducing area burned from the control fuels map using both statistical tests. As a qualitative assessment, FC treatments were less effective at reducing area burned in comparison to FI treatments. However converting a higher percentage and variety of flammable fuels resulted in statistically significant reductions in area burned. It is important to note that the removal of 7% of fuels would result in a direct reduction of area burned of up to 7%. However the reduction in area burned for fuel isolation treatments were above 50%, thereby demonstrating that the presence of fuel treatments significantly affected area burned outside of this direct affect.

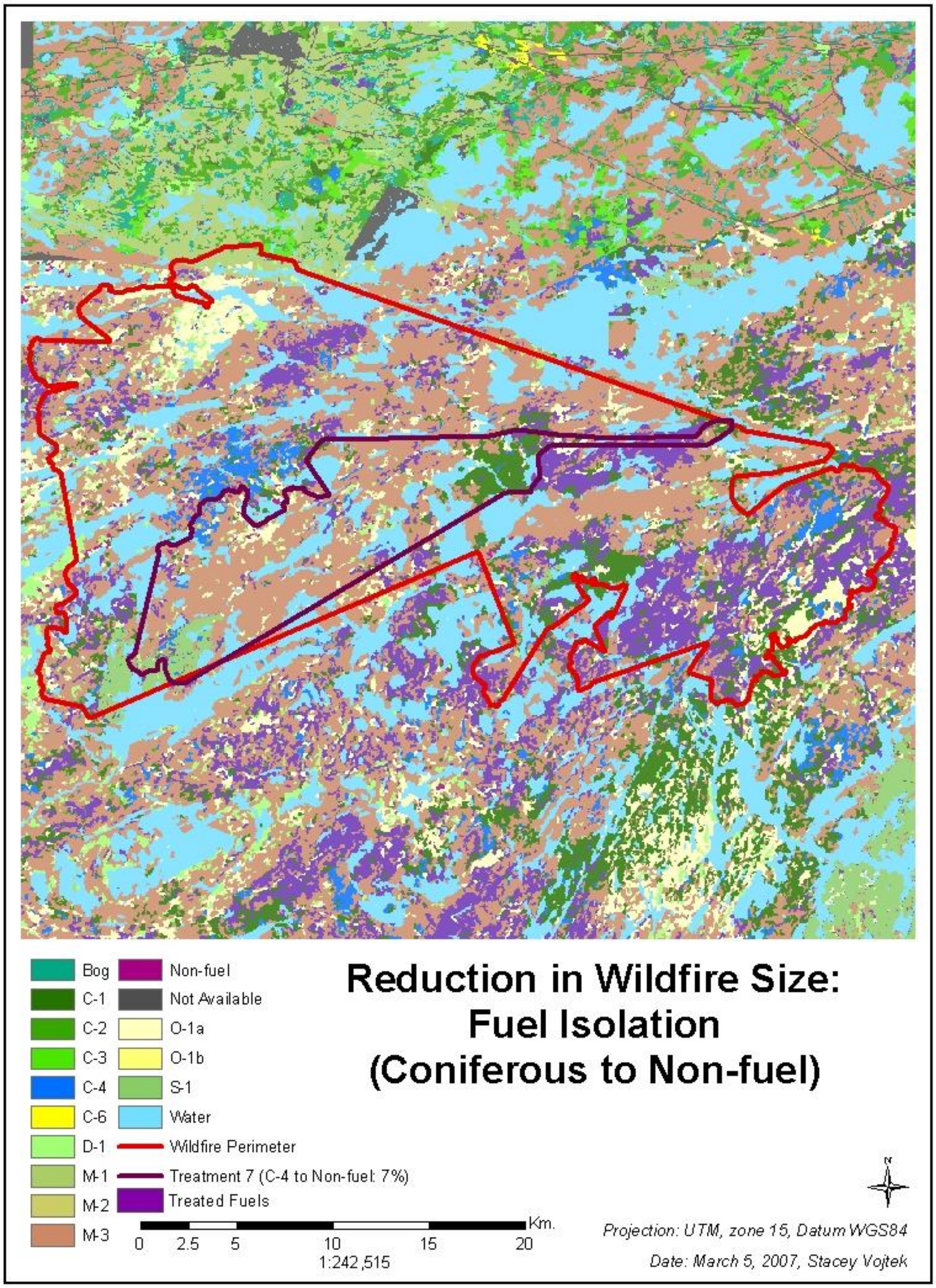

Figure 5.1 Fuel Isolation Treatment that resulted in considerable reduction in area burned.

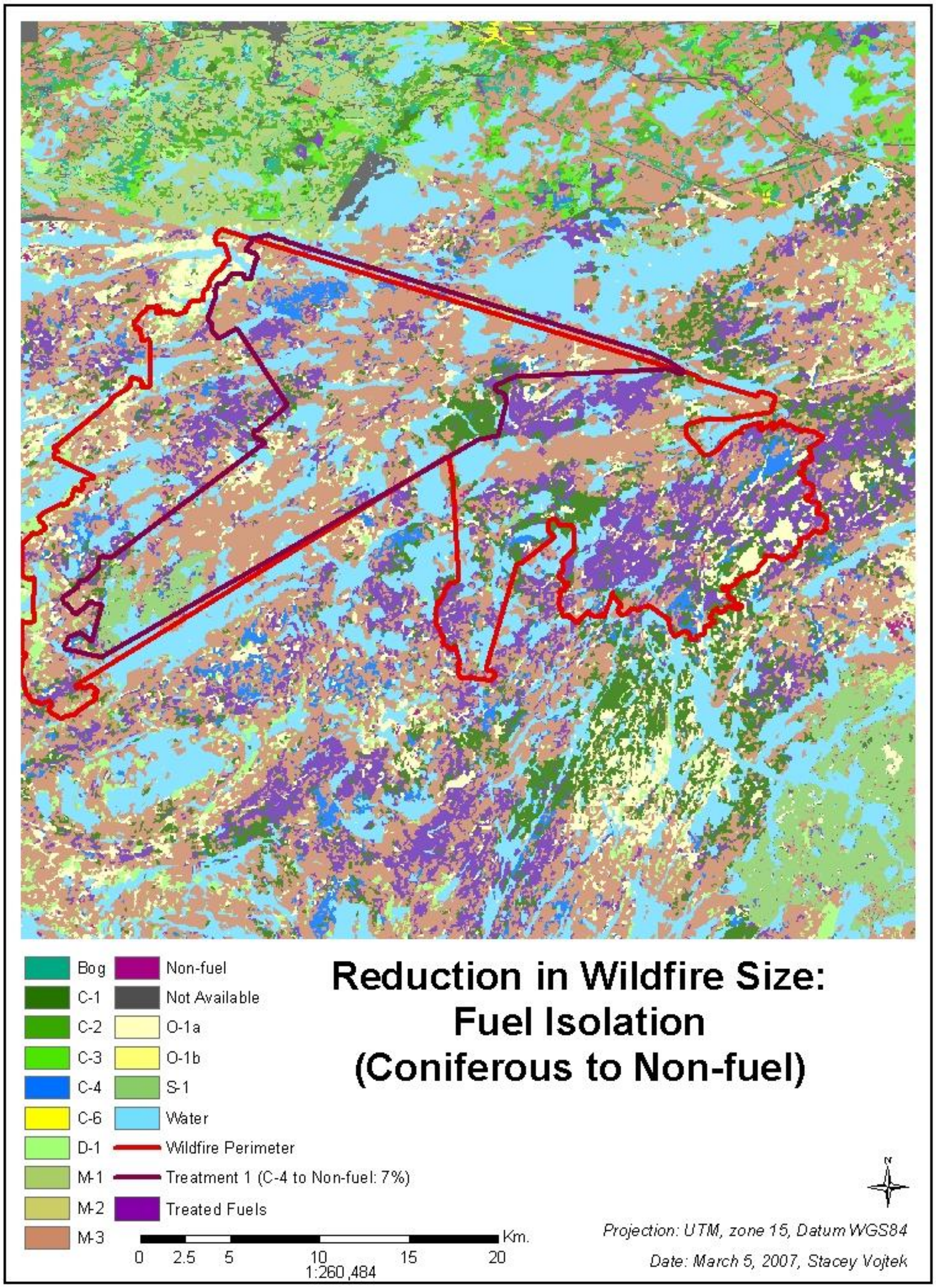

Figure 5.2 Fuel Isolation Treatment that resulted in minimal reduction in area burned.

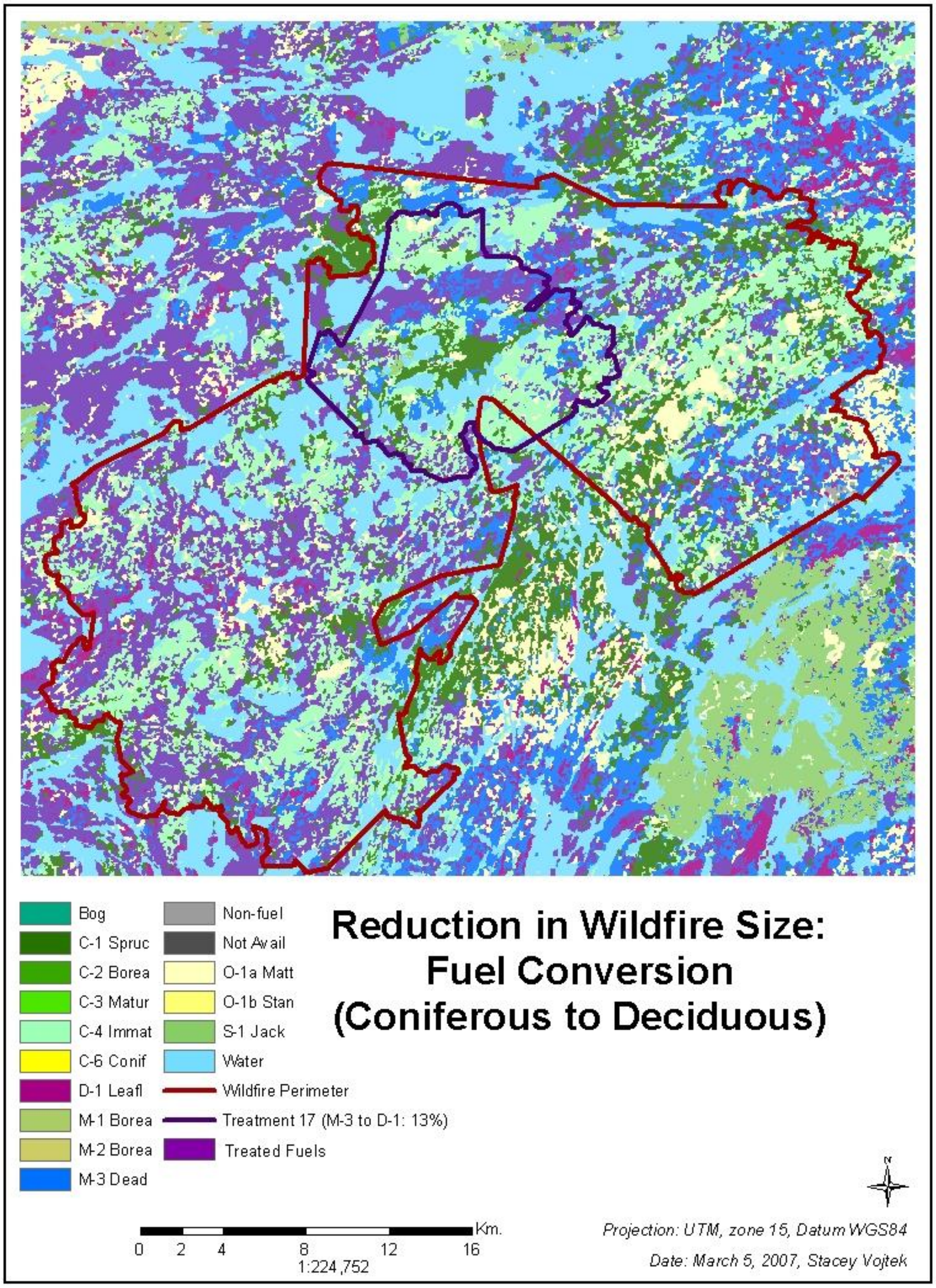

Figure 5.3 Fuel Conversion Treatment that resulted in considerable reduction in area burned. *Note: M-3 (75% dead fir (pdf)) was the fuel type converted in Treatment 17. All other M-3 fuel types (% pdf) are dark blue.

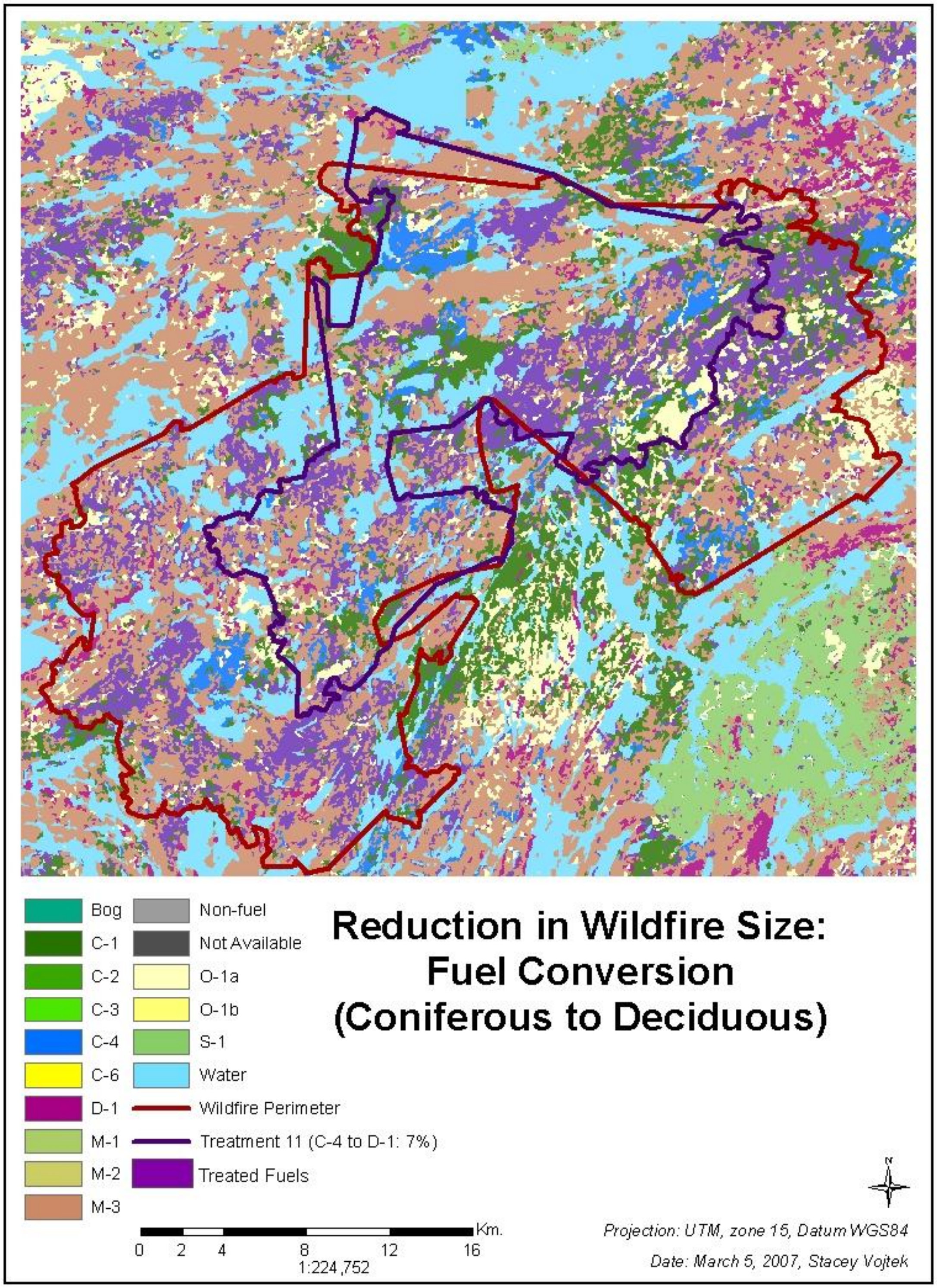

Figure 5.4 Fuel Conversion Treatment that resulted in minimal reduction in area burned.

To demonstrate the effectiveness of FI treatments in reducing area burned under extreme fire behaviour conditions in Quetico Provincial Park see Figure 5.1. The figure depicts one simulation run on the Control Fuels Map (Wildfire Perimeter) and on FI Treatment 7 (7% from Immature Jack Pine → non-fuel). The reduction in area burned is substantial, demonstrating FI is effective at reducing area burned under the constraints of this research. Figure 5.2 depicts the same ignition coordinate as Figure 5.1, with the Wildfire Perimeter from the Control Fuels Map and from FI Treatment 1. The fire perimeter for Treatment 1 is less effective at reducing area burned, however some fire reduction is achieved on the east flank of the fire, suggesting that FI acted as a fire break preventing the fire from growing easterly. Some fire perimeters have straight edges as a result of 2 factors:

1) By using a low smoothing factor setting in the Prometheus fire engine. As noted, all simulations were executed with identical fire engine settings; therefore the smoothing factor was not applied to any of the simulations. It was not used because the smoothing factor substantially increases computation time. The small-scale differences in shape when using the smoothing factor is not significant for this research, because this research focussed on the difference in area burned and not the shape of a fire perimeter.

2) The second factor is related to how Prometheus creates fire perimeter shapefiles. Prometheus, version 4.0.15, contained a problem with how fire perimeters were exported as shapefiles. Prometheus created a shapefile for export by connecting active fire vertices (and those that were active within the

last 90 minutes of the fire), but did not incorporate inactive fire vertices. For instance, if a fire reached a body of water, or non-fuel, the fire vertices were made ‘inactive’, and were ignored when creating the shapefile. This altered the final shape of the exported fire perimeter. However, inactive vertices were used when calculating area burned statistics, and did not impact this research. This is also the reason treated fire perimeters appear to have growth beyond the control fire perimeters in Figures 5.3 and 5.4. This problem was fixed in later versions of Prometheus (version 4.2+).

Figures 5.3 and 5.4 depict the effectiveness of FC on the reduction of area burned under extreme fire behaviour conditions in Quetico Provincial Park. Figure 5.3 illustrates the effectiveness of Treatment 17 (13% from Dead Balsam Fir Mixedwood → Leafless Aspen). These examples were chosen because the treatments are extremely effective at reducing area burned. Figure 5.4 depicts Treatment 11 (7% from Immature Jack Pine → Leafless Aspen) in comparison to the Wildfire Perimeter. This treatment was chosen because it is less successful at reducing fire extent in comparison to Treatment 17. Using maps to demonstrate effectiveness in reduction of area burned can be powerful, but single maps do not demonstrate statistical significance and overall effect of FI and FC treatments, and are therefore only used as a supplementary method of communicating observed results.

Figures 5.5 through 5.10 depict the distribution of wildfire size in the Control and Treatments 1 through 17 by weather stream. The minimum fire sizes are not depicted on the maps as they are too small to view in conjunction with the other distribution statistics.

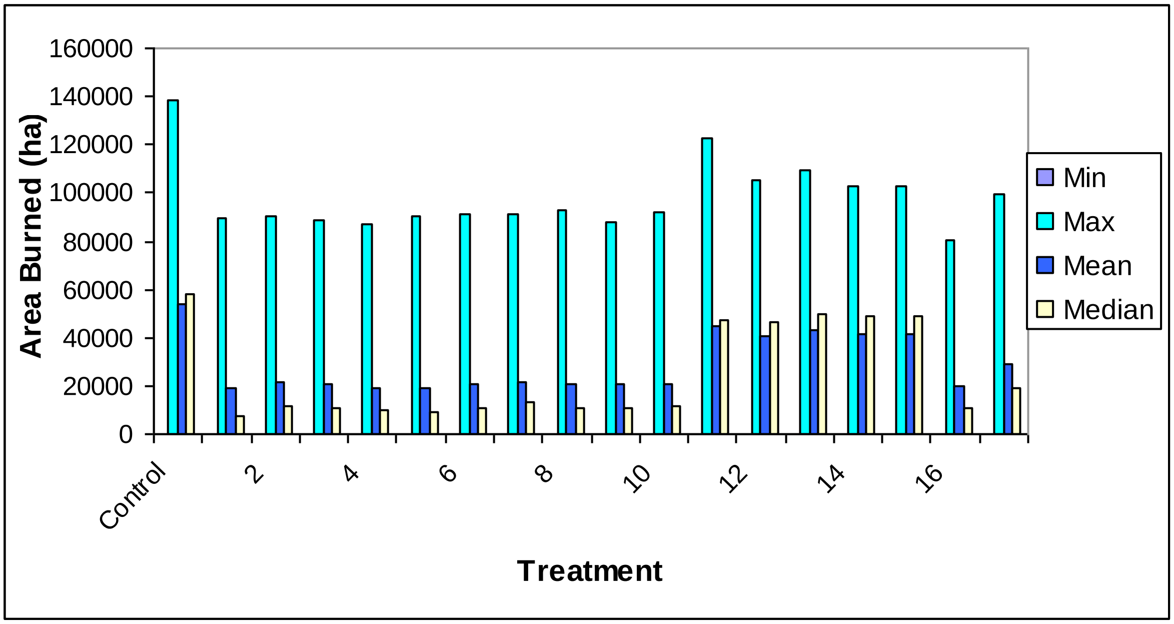

Figure 5.5 Distribution statistics of wildfire size for the April 9, 2003 Weather Stream.

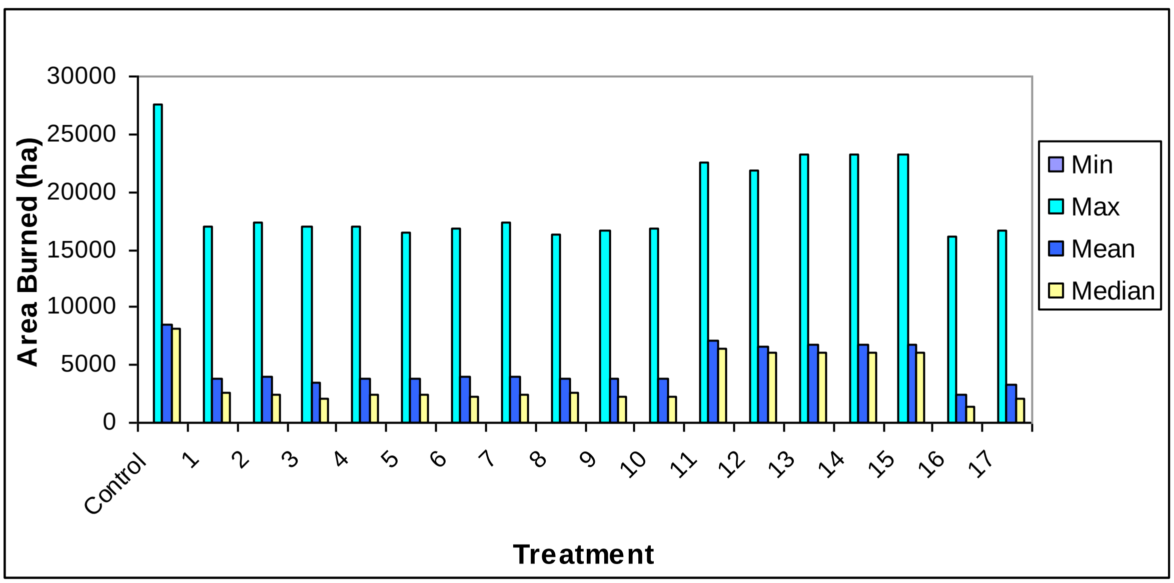

Figure 5.6 Distribution statistics of wildfire size for the May 10, 1998 Weather Stream.

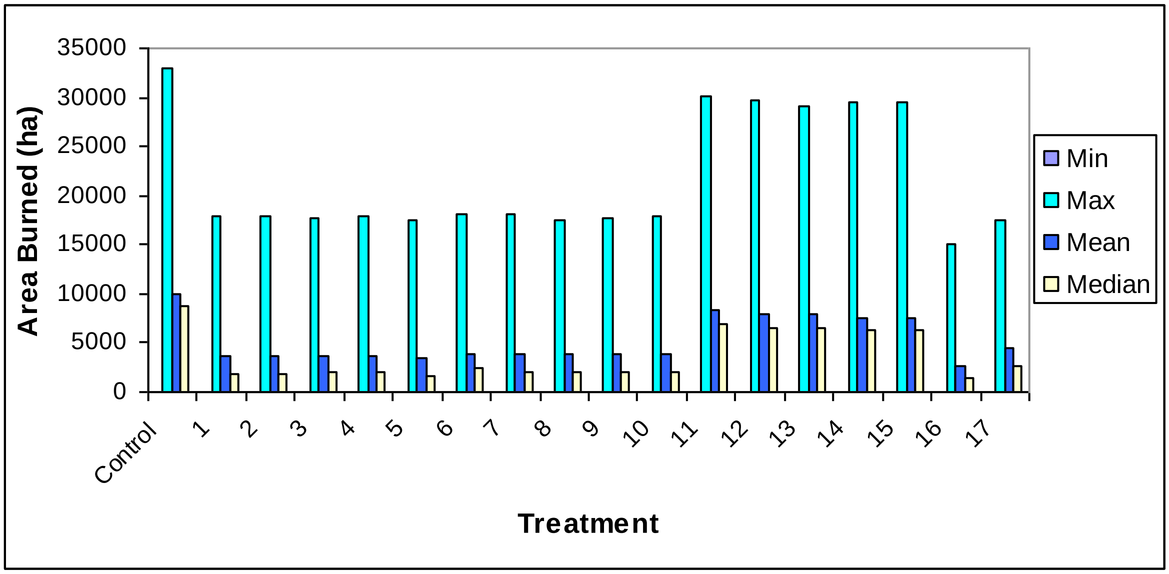

Figure 5.7 Distribution statistics of wildfire size for the August 20, 1995 Weather Stream.

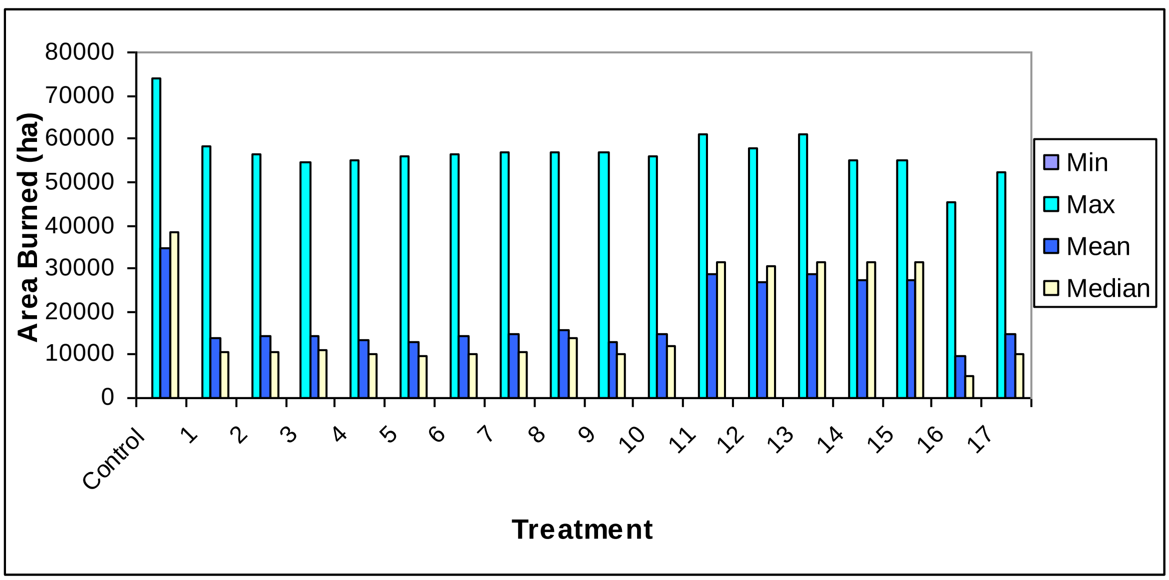

Figure 5.8 Distribution statistics of wildfire size for the July 1, 2001 Weather Stream.

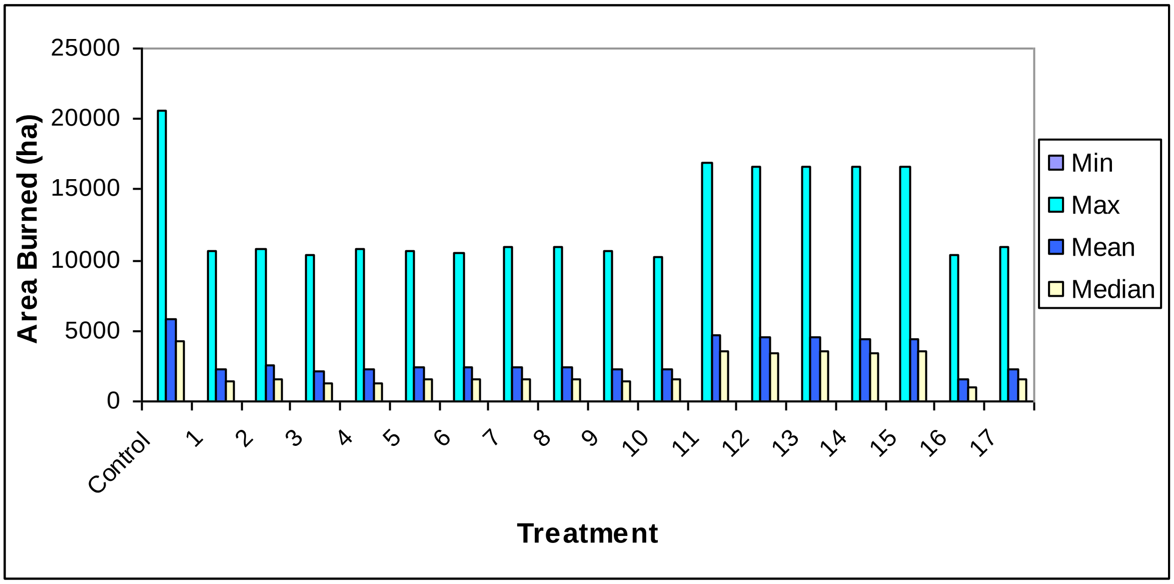

Figure 5.9 Distribution statistics of wildfire size for the May 14, 1999 Weather Stream.

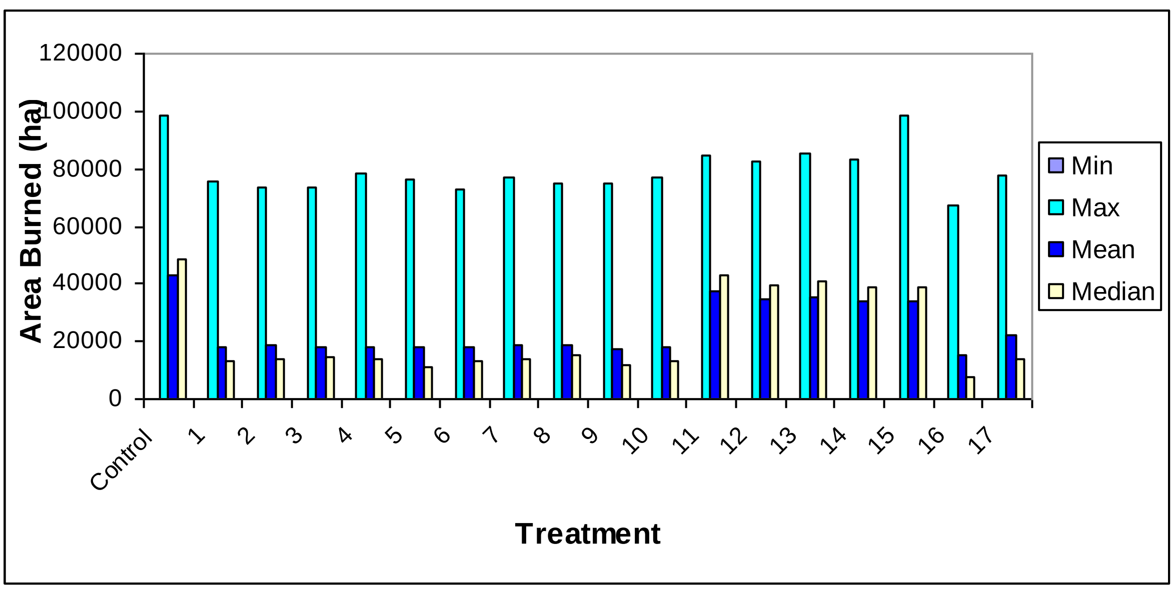

Figure 5.10 Distribution statistics of wildfire size for the May 19, 1994 Weather Stream.

5.1 Tukey's HSD test

In Tukey's HSD tests, all FI treatments for all weather streams and for the blocked analysis were effective at reducing area burned ($P < 0.0001$) compared with the control fuels map. See Table 5.1 and 5.2. All fuel conversion treatments were effective at reducing area burned compared with the control fuels map for the July 7 weather stream and the blocked analysis ($P < 0.0001$). All fuel conversion treatments were effective at reducing area burned compared with the control fuels map with the exception of Treatment 11 (FC from 7% Immature Jack Pine → Leafless Aspen) ($P < 0.0001$) for the April 9, May 10, May 14, May 19 and August 20 weather streams. See Table 5.1 and Table 5.2 Tukey's HSD and Dunnett's Tests results.

Table 5.1 Summary statistics for area burned by weather stream and blocked analysis based on Tukey's HSD and Dunnett's Tests with a 95% simultaneous confidence limit.

Weather Stream	Source of Variation	df	Sums of Squares Type III	F	P
Blocked Analysis	Date	5	2.4	1760.1	<0.0001
Blocked Analysis	area burned	17	6.60E+11	144.2	<0.0001
April 9, 2003	area burned	17	4.60E+11	35.4	<0.0001
May 10, 1998	area burned	17	1.10E+10	29.8	<0.0001
May 14, 1999	area burned	17	5.50E+09	32.1	<0.0001
May 19, 1994	area burned	17	3.00E+11	38.1	<0.0001
July 7, 2001	area burned	17	2.10E+11	51.2	<0.0001
August 20, 1995	area burned	17	1.90E+10	37.2	<0.0001

Table 5.2 Reductions in area burned resulting from FI and FC treatments compared with the control fuels map, measured in hectares and % for blocked analysis.

Treatment	FI and FC fuels	Difference from Control (ha)	% Change from Control	Tukey's HSD	Dunnett's
1	7% C-4 to non-fuel	15608.5	61	*	*
2	7% C-4 to non-fuel	14931.0	58	*	*
3	7% C-4 to non-fuel	15447.3	60	*	*
4	7% C-4 to non-fuel	15781.6	61	*	*
5	7% C-4 to non-fuel	15817.2	61	*	*
6	7% C-4 to non-fuel	15198.8	59	*	*
7	7% C-4 to non-fuel	14820.9	58	*	*
8	7% C-4 to non-fuel	14914.1	58	*	*
9	7% C-4 to non-fuel	15700.7	61	*	*
10	7% C-4 to non-fuel	15192.3	59	*	*
11	7% 4 to D-1	4098.5	16	**	***
12	8.8% C-4 to D-1	5563.1	22	*	*
13	17.1% C-4, C-1 to D-1	4875.8	19	*	*
14	21.9% C-4, C-1, C-2 to D-1	5552.3	22	*	*
15	25.2% C-4, C-1, C-2, C-3 to D-1	5542.9	22	*	*
16	38.2% C-4, C-1, C-2, C-3, M-3 to D-1	17275.1	67	*	*
17	13% M-3 to D-1	13200.7	51	*	*

*Indicates statistical significance at $P<0.05$.

**Treatment 11 was significant for weather stream July 7, 2001 and for the blocked analysis in the Tukey's HSD test.

***Treatment 11 was significant for all weather streams but May 19, 1994 for the Dunnett's test.

5.2 Dunnett's Test

In Dunnett's tests, for all weather streams and the blocked analysis (except Treatment 11 (FC from 7% Immature Jack Pine → Leafless Aspen for the May 19 weather stream (P <

0.0001)), both FI and FC are effective at reducing area burned compared with the control fuels map ($P < 0.0001$). See Table 5.1 and Table 5.2.

As a qualitative observation, FC becomes more effective in reducing area burned as more fuels are converted. See Figure 5.11. A substantial change in effectiveness does not occur until a 38.2% FC treatment in comparison to the 25.2% FC. Treatment 16 (38.2% FC from all conifers and Dead Balsam Fir Mixedwood → Leafless Aspen) and Treatment 17 (13% FC from Dead Balsam Fir Mixedwood → Leafless Aspen) are effective at reducing area burned compared with the control fuels map for all weathers streams and the blocked analysis ($P < 0.0001$). The reduction of area burned from these two treatments is comparable to reductions caused by FI treatments. See Figure 5.11 and 5.12.

Tukey's HSD tests show FI treatment effects were not significantly different from each other ($P < 0.0001$). This was expected, as there is a total of 8.8% Immature Jack Pine on the landscape. Therefore there would be limited differences in the 7% FI treatment patterns between Treatments 1 through 10. For this research, this implies the pattern of random fuel treatments likely did not substantially affect area burned. Using the same test the 7%, 8.8%, 17.1%, 21.9% and 25.2% FC treatments were not significantly different from each other ($P < 0.0001$). It was not possible to test whether the pattern of FC was a contributing factor to the reduction of area burned, due to the varying percentage of fuels converted for FC treatments.

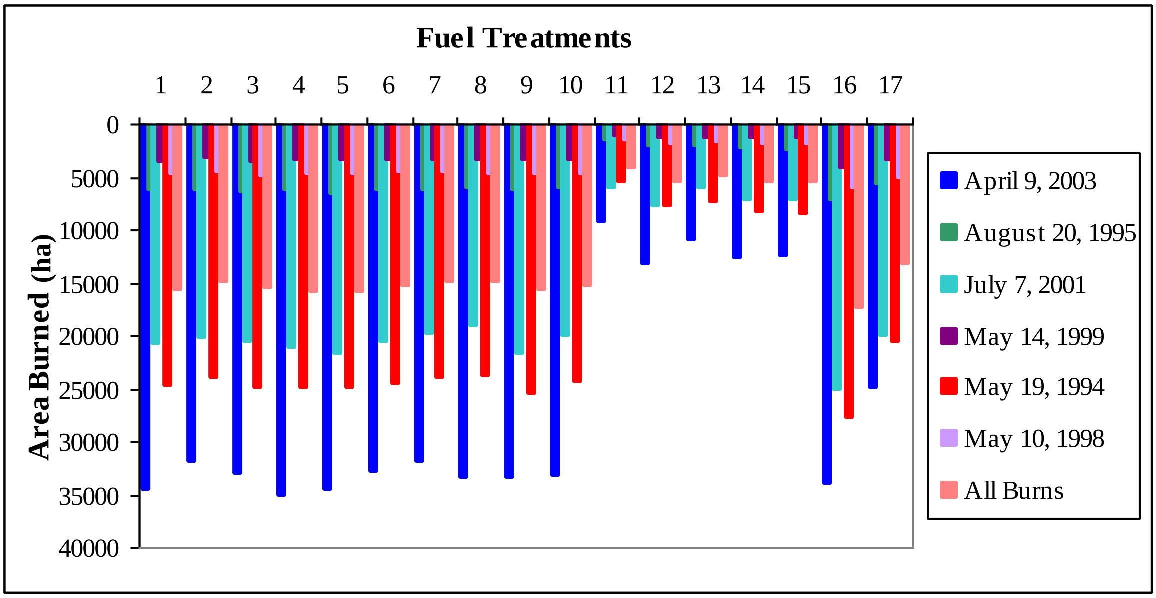

Figure 5.11 The differences in area burned in hectares between treatments and the control fuels map based on results of Tukey's HSD and Dunnett's tests by weather stream dates and blocked analysis (All Burns).

As a general observation, longer weather streams produced larger area burned. Though this may be common knowledge in the field, the effects of weather stream length have not been studied in fire growth modelling. July 7 weather stream has 87 time steps (one of the longer weather streams used in this research). Using both statistical tests, we see that a 7% FC treatment from Immature Jack Pine → Leafless Aspen is effective in reducing area burned ($P < 0.0001$). This may indicate longer extreme wildfire events require a smaller percentage of FC to reduce area burned. However, this would have to be substantiated with more treatment tests.

Overall, FI treatments were effective at reducing average area burned from the control by about 53-65%. FC treatments have a greater range of variation in percent effectiveness, ranging from 18-73%. The conversion from Dead Balsam Fir Mixedwood → Leafless Aspen was most effective at reducing area burned from the control (73%). This was expected due to the volatile nature of this fuel. Treatment 11 (7% FC from Immature Jack Pine → Leafless Aspen) has the lowest percent change in area burned from the control for FC treatments (18%). This is an important observation if any amount of area burned reduction is desirable.

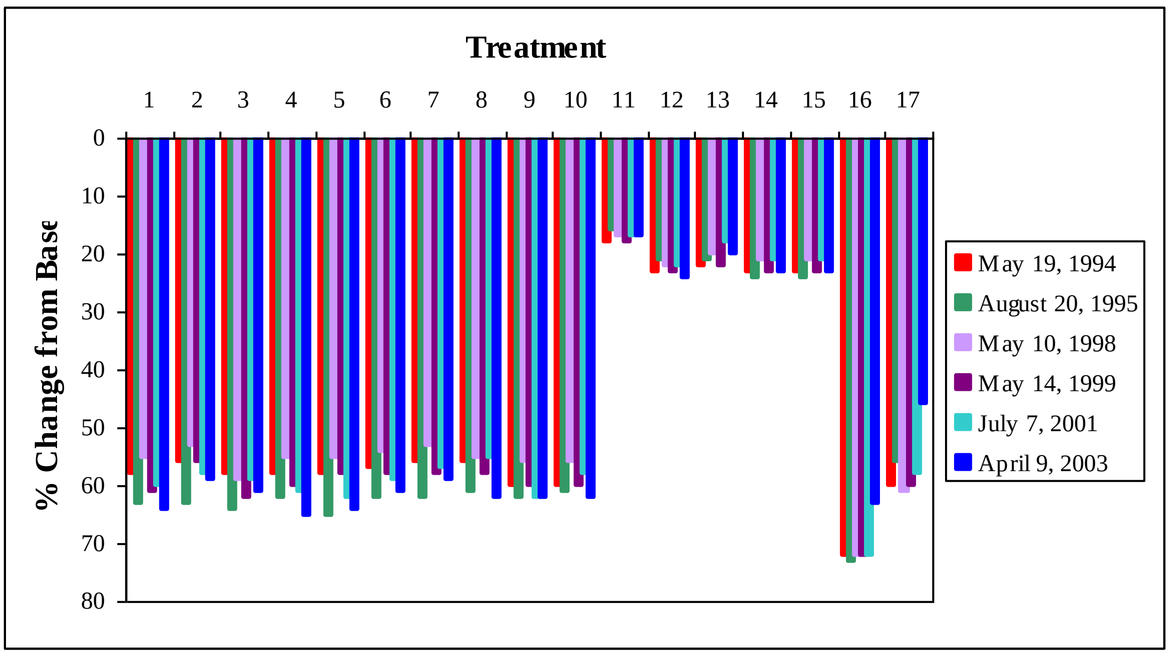

Figure 5.12 Percentage change in average area burned between the control fuels mpa and treatments by weather stream dates.

Chapter 6
Discussion

This research examined whether randomly fragmenting highly flammable fuels in the boreal forests of Quetico Provincial Parks decreases average area burned under extreme fire behaviour conditions. These conditions were simulated using a fire growth simulation model, with a particular emphasis on three research questions.

First, I addressed whether isolating highly flammable boreal forest fuels decreases average wildfire size in Quetico Provincial Park under extreme fire behaviour conditions. Using both Tukey's HSD and Dunnett's tests, all FI treatments significant reduced area burned compared with the control, ranging from approximately 53-65% reduction in area burned. Therefore the answer to the first question is yes, isolating fuels by converting 7% of the landscape from Immature Jack Pine to non-fuel is effective at reducing average area burned by at least 50% in Quetico Provincial Park under extreme fire behaviour conditions.

The fuel treatments in this study were not strategic bulkhead treatments, nor were they completely random, as treatments were targeted in flammable fuels. Forest stands do not grow randomly, as they are affected by such factors as ecological disturbances, nutrients, topography and microclimatic conditions. Therefore targeting certain stand types (e.g. flammable coniferous fuels) partially removes the random component of treatment patterns. However, within the targeted fuel types (Immature Jack Pine), stands were randomly chosen for FI treatments. FC Treatments targeted known types of flammable stands (all coniferous stands and Dead Balsam Fir Mixedwood) opposed to mixed stands and deciduous stands with lower flammability characteristics. Thus treatments were not truly random, nor were they strategic bulkhead (fire break) treatments.

The second question was whether fuel conversion (from coniferous to deciduous) decreases average wildfire size in Quetico Provincial Park under extreme fire behaviour conditions. Using both Tukey's and Dunnett's tests, fuel conversion is effective at reducing average area burned under extreme fire behaviour conditions, with a greater range of variation in effectiveness than with FI treatments, ranging from 18-73% reduction in area burned from the control. Tukey's HSD test indicates Treatment 11 (FC 7% Immature Jack Pine → Leafless Aspen) was the only treatment that did not significantly decrease average area burned in five of the weather streams, as was the case with the Dunnett's test for the May 19 weather stream. For Quetico Provincial Park, converting over 8.8% of the landscape from highly flammable fuels to less flammable fuels is effective at reducing average area burned in extreme fire behaviour conditions.

In heterogeneous landscapes, gross fire spread rate and shape should be calculated based on properties of fuels and their topological arrangements as fires can burn laterally around obstacles (Finney, 2003). The flammability of the fuels is critical to the development of the rate of spread, and therefore the fire extent, as fires progress more directly through highly flammable fuels due to a faster forward rate of spread. They progress more slowly, by flanking around patches of less flammable fuels (Finney, 2003). It is likely for this theory that fuel conversion confers success in reducing average wildfire extent in this study.

In addition to conversion of Immature Jack Pine, other flammable fuels were converted as outlined in the methodology in order to increase the % of flammable fuel conversion. Of particular interest is that removal of M-3 (Dead balsam fir mixed-wood, leafless, 75% dead fir (pdf)) drastically reduced average area burned. This fuel type constitutes 13% of Quetico Provincial Park's landscape. It is often used to represent the resulting forest type after a major insect infestation such as spruce budworm in Quetico Provincial Park. In this research, removal of this fuel resulted in approximately 73% reduction in area burned. To put this in a different way, an increase in insect infestations would substantially increase area burned in Quetico Provincial Park. With an increase in a variety of insect infestations across the boreal ecotone in Canada, area burned may increase substantially and development of new fuel management techniques will be critical. With a warming climate due to climate change effects, the mountain pine beetle has begun moving easterly breaching the Rocky Mountain geo-climatic barrier (Carroll, 2007). Due to an increase in suitable habitat, composed of hybridized lodgepole and jack pine stands, there is potential for a mountain pine beetle invasion into the boreal forests (Carroll, 2007), increasing concern over interaction between insect infestations and wildfire extent.

Third, this research demonstrates that as a conceptual basis, fuel isolation and conversion are effective at reducing average area burned under extreme fire behaviour conditions in this region of North-western Ontario. This suggests that further research on fuel isolation and conversion as a prescriptive, proactive strategy is warranted.

6.1 Fuel Isolation and Conversion can address Climate Change Effects on Fire Regime

Climate change is affecting all ecosystems, including Canada’s boreal forests with both ecological and economic consequences. Functional changes are expected in biomass production, decomposition, nutrient turnover rates, carbon sequestration and susceptibility to disturbances such as disease, insect infestations and alterations in fire regime (Overpeck, Rind & Goldberg, 1990; Weber & Flannigan, 1997).

An altered fire regime due to a warming climate will cause immeasurable problems for land managers ranging in issues from adaptive fire management strategies, forest age mosaic alterations, biodiversity, carbon cycling and sequestration (Stocks et al., 1998; Weber & Flannigan, 1997). Though climate change will directly affect other ecological functions and processes, the increasing changes in regional fire regimes will likely overshadow other implications (McCoy & Burn, 2005; Weber & Flannigan, 1997).

With a likely increase in extreme weather events, and regional increases in fuel loads due to effective fire suppression, and increased insect outbreaks (Gollberg et al, 2001), situations that usually give rise to extreme fires; a doubling in area burned is a plausible (Gillett et al., 2004). Debate over the degree of change exists (McCoy and Burn, 2005). An increase in extreme fire behaviour conditions could result in fires with very high intensities and growth rates. These fires are difficult if not impossible to suppress. For instance, Hirsch and Martell (1996) found that suppression capabilities are futile beyond 10 000 kWm^{-1}. Extreme wildfire events frequently surpass this level, making fire control difficult using traditional fire suppression methods. The concept of fuel isolation and conversion may prove useful in helping to address the increase of wildfire extent as a result of climate change. Further research into the prescriptive applications is needed in order for natural resource planners to implement these strategies into policy and management programs.

6.2 Fuel Management for Protected Areas, Timber Resource Areas and the Wildland Urban Interface

Managing wildfire risk effectively is of great value to society, as wildfires can cause significant loss of life and high economic damage (Clarke et al., 1994; Loehle, 2004). The effects of wildfire can be viewed as either negative or positive, depending on the associated values at risk, and society's acceptance of resource management objectives (Hirsch et al., 2004). Public safety and timber values usually trump ecological values at risk; therefore the challenge facing fire and resource managers is to balance these risks and benefits on a site-specific basis (Hirsch et al., 2004).

Ecosystem resilience is an important concept natural resource planners must recognize, because as natural resilience declines ecosystems become vulnerable. This can enhance the effect of small external events on the system, causing shifts in system processes and structures (Folke et al., 2004). Ecosystem shifts are becoming more common as human activities continue to alter ecosystem processes and structures, through such activities as fire suppression and the effects of climate change. These influences may cause a fire regime shift in the boreal forest ecotype. Natural resource agencies frequently use pre-European fire regimes as a baseline for fire management goals. This shift may include larger, more severe and intense wildfires, beyond those experienced prior to European settlement.

Though large, stand replacing fires are ecologically desirable in boreal forests, striking the balance between the reintroduction of landscape level fires and limiting the negative effects of extreme wildfires caused by climate change and historical fire suppression is difficult. The reality is that sometimes regime shifts are irreversible (Folke et al., 2004). It is difficult to determine if that is the situation in the forests of North-western Ontario. However the precautionary principle dictates that we should act proactively to avoid such a shift. To reiterate, a shift of this proportion would include extreme wildfire events beyond what was natural prior to the human influences of fire suppression and climate change. The intent is not to limit all stand replacing fires across the landscape, but instead massive fire events that threaten ecological integrity and values at risk that are difficult to control with traditional fire suppression methods.

With an increase in frequency of extreme fire events, pressure on fire management agencies will continue to mount to balance fire suppression costs, values at risk and ecological integrity. To address these issues natural resource planners must look for alternatives to status quo fire management practices. Random fuel isolation and conversion of highly flammable fuels may help protected area managers reestablish historic fire regimes, through proactive fuel treatments that reduce average wildfire size in their landscapes. In theory, to return to historic fire regimes protected area managers could implement a fire management strategy that allows some wildfires to grow without using direct fire attack, thus reducing fire return intervals for the landscape, and assisting in the reintroduction of stand replacement fires.

This research converted fuel polygons from highly flammable fuels to non-fuel or deciduous fuels. The size and extent of these treatments varied considerably, based on the size of the polygons randomly (representing forest stands) chosen and the % of the landscape converted. The large size of treatments and complete removal of some coniferous stands would have substantial ecological implications. For this reason, further research is needed using smaller treatments across the landscape prior to implementation of prescriptive fuel management strategies in protected areas.

In the future, protected area planners may implement random fuel treatments through a series of prescribed fires of varying sizes targeting fire behaviour that favours the regeneration of deciduous species. This would reduce available fuel for combustion and break the continuity of fuel across a landscape. Replanting deciduous species could follow to promote fuel conversion. Timber harvesting is generally not an accepted practice within protected areas. However in protected areas where harvesting is allowed, this method could be used in combination with prescribed fires and replanting could be used to achieve fuel isolation and conversion. Direct fire suppression techniques would then be more effective if fire did reach values at risk or park boundaries, as the fires would be smaller in size. By reducing area burned from extreme wildfire events, while still allowing stand-replacing fires, natural resource planners can assist boreal forests in returning to a pre-anthropogenic climate change and pre-fire suppression fire regime state. This may lead to returning to a more natural range of disturbance effects, and act as a long term, landscape level restoration.

Implementing fuel management at a landscape scale has evolved partly out of a response to timber shortages resulting from uncontrollable wildfires, as timber is increasingly becoming a limited resource in Canada (Hirsch et al., 2004). Unwanted wildfires cause an estimated $2 B cdn in timber losses (de Groot, Bothwell, Carlsson & Logan, 2003), further threatening the livelihoods of many Canadians (Hirsch et al., 2004). Therefore the forestry sector should consider testing the use of scattered fuel treatments to protect valuable timber resources from extreme wildfire events.

Millar Western Industries (MWI) in Whitecourt, Alberta, is incorporating fuel management into their short-term forest management activities in order to address the issue of timber loss during extreme wildfire events (Hirsch et al., 2004). Other timber companies might consider following this example, and adapt their current cut-block rotation and regeneration practices to include fuel isolation and conversion to reduce landscape flammability.

Hirsch et al. (2004) describe a landscape level approach for reducing the spread of wildfires with the implementation of *strategically* located reductions of highly flammable fuels, which serve as anchor points for fire suppression. The suggestion is to use fuel conversion to alter the flammability of these fuels, though this would be difficult to do nationwide (Amiro, Stocks, Alexander, Flannigan & Wotton, 2001). If this was implemented throughout timber resource areas over time, a reduction in the size of wildfires under extreme weather conditions is possible (Hirsch et al., 2004). My research shows that *random* fuel isolation and conversion are possible avenues for reducing landscape flammability in boreal forests. Active timber resource areas provide an excellent field research opportunity to test these fuel management concepts. If implemented as part of their overall replanting and regeneration plan, natural fire events would provide opportunities to study these concepts in the field.

Fuel treatments, achieved through a series of thinning and harvesting operations of immature pine stands, could have a dual purpose: 1) A reduction in wildfire extent thus limiting the threat to mature timber resources, and 2) Providing timber for use as biomass feedstock in electric power production. In 1992, the United States formed a National

Biofuels Roundtable partly to address the development of biomass production at a landscape scale (Turnbull, 1994). Biomass production might help to address other environmental concerns by displacing significant amounts of fossil resources, thus reducing the amount atmospheric carbon dioxide that contributes to anthropogenic climate change effects (Turnbull, 1994). Typical woody species for biofuels production are hybridized poplars, black locust and sliver maple. The effectiveness of pine species for biofuels purposes should be studied in depth to determine if this is a viable spin off activity of fuel treatments in the forestry industry.

A variety of fuel management may help mitigate threats of extreme wildfire events to interface communities. Wildfires are increasingly threatening lives and infrastructures in wildland urban interfaces, such as the 2003 British Columbia Firestorm interface fires, which destroyed 334 homes, caused the evacuation of over 45,000 people and amassed damages estimated at $700 million (Filmon, 2003). Fuel management based on a strategic bulkhead FireSmart community protection approach is being tested in a few Canadian interface communities. However, the reduction of fuel immediately surrounding buildings and the community interface may not suffice to protect values at risk during extreme wildfire events.

In theory, fuel isolation and conversion could be used surrounding communities and extending past the reach of traditional FireSmart community protection boundaries. In addition to strategic bulkhead fuel management approaches of FireSmart community protection, this research demonstrates in theory that random treatments of surrounding forested landscape would help to reduce average wildfire size as it approaches a community. If a fire does reach the community, traditional suppression capabilities may be employed to further protect the community. Perhaps a combination of the FireSmart community protection approach with random fuel isolation or conversion treatments would provide the greatest level of protection for community interfaces.

At a landscape scale, fuel treatments could be difficult due to limited funding, public controversy, inadequate road access, variable land ownership, and opposing regulations (Finney, 2001; Keane et al., 2003; Loehle, 2004). Though this is not a strong enough argument to do nothing; extreme wildfires pose a real risk that needs to be addressed. Priorities of treatments could be based on local hazards, ecological objectives, convenience, cost, accessibility, and land ownership (Finney, 2001; Pollet & Omi, 2002; Stephens, 1998).

Before this research can move from a conceptual approach to a prescriptive management strategy for protected areas and interface communities, further research is needed on the impacts of fuel management on other ecological components, such as water quality, habitat composition and fragmentation, soil compaction, biodiversity, essential ecosystem functions and alteration of forest composition and structure (Martell et al., 2004). How fuel management affects wildlife is unknown, particularly in regards to aquatic ecosystems, though progress has been made (Riemen, Luce, Gresswell & Young, 2003). The continued lack of understanding of the effects of fuel management strategies on fish and wildlife will impede the development of ecologically sound management practices (Bury, 2004). Future studies should consider full effects of fuel treatments on the quality and quantity of post-treatment habitat, including consideration of amount of leaf litter and downed wood after fire, and if wildlife concentrate in remaining usable habitat (Bury, 2004).

The risks of wildfire need to be weighed against these potential negative effects of fragmentation. Martell et al. (2004) studied the effects of fuel fragmentation on wildlife in relation to timber harvesting, and found that FireSmart forest management may produce more habitat than current forestry practices, but not as much habitat as not allowing timber harvesting at all in some forests. Further research is needed to examine the effects of fuel management strategies on ecological health and wildlife species, on a site-specific basis. A significant challenge of fuel treatments will be shifting the perception of these practices, and implementing effective ecosystem management by balancing ecological integrity and economic development (Hirsch et al., 2004; Partners in Protection, 2003).

6.3 Future Research

The results of this conceptual research suggest the need for further research into random fuel treatments prescriptions in boreal forests across Canada. This research should be replicated for sites that are representative of regional boreal forest fuel structures to determine if fragmentation is effective at reducing average wildfire size in other landscape contexts. For instance, Quetico Provincial Park is naturally fragmented by a diverse system of lakes and waterways, which likely had an affect on the percentage of fuel isolation and conversion needed to significantly reduce average wildfire size. Repeating this research in areas with more continuous boreal fuels, e.g. Wood Buffalo National Park, would be beneficial to the establishment of random fuel treatment theory and associated minimum thresholds. Quetico Provincial Park is only one case study in a multitude of possible site locations that could benefit from implementing landscape level random fuel treatments.

Research should focus on how topography and existing landscape fragmentation affects the amount of fuel isolation and conversion needed to substantially reduce average area burned. As well, this research could be applied in a more conceptual landscape to systematically determine which fuels, or fuel combinations, are most efficient at reducing area burned.

If fire management planning is to be successful, the use of fire growth modelling should be incorporated in the planning environment (Hessberg, Agee & Franklin, 2005), in addition to large-scale field experiments. However, further research is needed on how to define simulation start and end parameters as well as how to configure weather streams to mimic fire growth periods. I have observed that the number of time steps may affect size of extreme fire events. The pattern of change between area burned in the control and fuel treatments remains the same regardless of length of weather streams. April 9 is the longest weather stream (153 time steps), and resulted in highest average area burned. May 14 is the shortest weather stream (36 steps), and resulted in lowest average area burned. Though it is obvious that longer weather streams result in greater area burned, further research is needed on determining weather stream parameters, including length, for use in deterministic modelling research. Currently, Prometheus does not turn fires "off" until the user ends the simulation or until the weather stream ends. This important end date is determined for either tactical reasons, or based on user-defined rules developed to mimic the ebb and flow of fire growth. The development of these rules requires further study.

An increase in size of extreme wildfire events may also result in wildfires with extreme intensities. Further research on this is needed because although fires can be ecologically beneficial, fires that are very extreme in intensity can sterilize the soil of microorganisms, thereby impacting the ecological health of the area (Clarke et al., 1994). A potential increase in wildfire size, frequency and intensity is also cause for concern as fires are a major source of gasses and particulates in the atmosphere, causing an increase in greenhouse gas effects (Clarke et al., 1994), thus potentially creating a positive feedback loop and enhancing the effects of climate change on fire regime.

To summarize, future research is needed to validate the prescriptive basis for fuel isolation and conversion and to determine the extent to which these strategies could be applied. Additional research should include:

- Random fuel isolation and conversion should be studied in conjunction with strategic fuel treatments (FireSmart community Protection) for effectiveness of protecting timber resources and other values at risk near communities and infrastructure.
- How random fuel treatments affect wildfire intensity and severity.
- Developing rules to determine fire ignition and extinguishment parameters for the fire growth simulation environment.
- Determining if random fuel treatments are effective at reducing average wildfire size under moderate and high fire behaviour conditions. This would determine if treatments would help reduce the overall degree of direct fire suppression needed under all wildfire conditions, and if they would be detrimental to ecological values by limiting the effects of smaller wildfire events.
- Future research should also focus on examining how fire shape and patchiness is

altered by fuel treatments. As well, the shape of the fuel treatments may influence the fire-spread capability and should be explored further using fire growth models.

This research potentially had implications for the management of boreal forest landscapes, both for resource management and human safety.

6.4 Conclusions

Despite continued suppression efforts, wildfires have occurred on the landscape under extreme fire behaviour conditions over the past century (Agee & Skinner, 2005; Finney et al., 2005). As fire suppression has limits in effectiveness, extreme large fires could escape control (Martell, 1996). With climate change potentially increasing these severe fire behaviour conditions, area burned is expected to increase substantially. These fires potentially threaten 1) Ecological values in protected area landscapes, 2) Timber resources, and 3) Interface communities.

Through the use of fire growth modelling, I tested the use of fuel isolation and conversion treatments in a subsection of the boreal forests of Quetico Provincial Park. By converting 7% of the landscape from Immature Jack Pine to non-fuel, average area burned was reduced from the control by 53-65%. Converting highly flammable fuels to Leafless Aspen saw a reduction in average fire size from the control of 18-73%.

These results demonstrate that fuel isolation and conversion are effective fuel management concepts in the reduction of average area burned under extreme fire behaviour conditions. These results, though specific to the Quetico Provincial Park region, indicate that random fuel isolation and conversion of highly flammable fuels should be studied further as a prescriptive fire management strategy to reduce the risks of increased area burned. As fuel treatments will not completely protect values at risk from wildfire, fuel management should be part of an integrated fire management strategy that includes prevention of human-caused fires, and efficient fire detection and suppression (Fernandes & Botelho, 2003).

The following recommendations are based on the demonstrated success of random fuel treatments in this research:

- Further research is needed on the use of random fuel treatments in protected areas. The size and extent of fuel treatments needs to be further refined before prescriptive implementation in protected areas. However, protected area planning should not ignore the potential of random fuel treatments to reduce average wildfire size within park boundaries. By limiting their size proactively, park managers may one day limit risk of wildfires escaping their boundaries while allowing stand-replacing fires within the interior of the park. This would also reduce the necessity of direct fire suppression for a greater number of wildfires.
- Timber production should consider the use of prescriptive random fuel treatments to reduce the potential loss of timber values to large wildfires. By incorporating fuel treatments into their cut blocks through thinning and fuel conversion, they may limit the average area burned from escaped wildfire and reduce their economic risks.
- Fuel treatments should be research further for implementation in landscapes surrounding communities and other values at risk to reduce the risk of wildfires

threatening human safety and infrastructure. It is expected that the degree of reduced wildfire risk is proportional to the decrease in average extreme wildfire size. Therefore other fire management strategies should not be abandoned for random fuel treatments. Instead a comprehensive, long-term planning strategy that includes random fuel treatments should be studied further and potentially implemented.

Landscape scale management approaches may be applied across a large portion of Canada's boreal forest and potentially in other countries, as the boreal forest ecotype is far reaching. Though fire growth modelling was done at the landscape scale in order to include the appropriate level of detail, the findings could have regional level implications for management.

Fire management planning in Canada is an evolving applied science. Fire management is beginning to bridge the gap between reactive fire strategies and progressive fire management planning. To address the issue of increasing extreme wildfire events, it is imperative that planners consider alternatives to direct fire suppression. Random fuel isolation and conversion area plausible management strategies that could be applied for a variety of resource protection initiatives. Without effective, long-term planning for fuel management in boreal forests, extreme wildfires will continue to threaten human life, values at risk and potentially ecological integrity.

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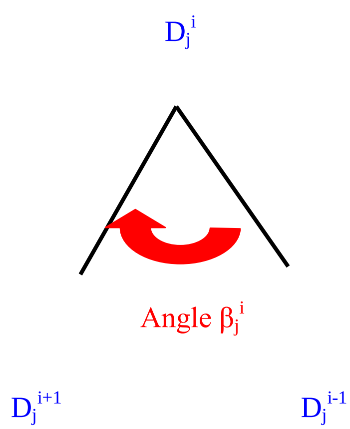
Appendix A
Glossary

Angle Threshold: The angle and distance threshold values control the number of vertices that are added between major vertices. As the angle threshold value (in degrees) decreases, more vertices are added. The end result is a smoother elliptical perimeter. However, more vertices will increase the number of calculations and reduce the overall speed of the model (Anonymous, 2007). The point insertion technique is executed when the angle between a vertex and its two neighbouring vertices, divided by the distance between the two neighbouring vertices, is less than the angle threshold value.

Insert Points When:

Angle β_j^i / Distance $(D_j^{i-1}, D_j^i, D_j^{i+1}) <$ Angle Threshold Value



The angle threshold is applied to both convex and concave angles on a fire perimeter. This threshold forces more points to exist in areas of the fire perimeter exhibiting high angularity (McLoughlin, 2007). This function is no longer used in the newer versions of Prometheus.

Buildup Index (BUI): A numerical rating of the total amount of fuel available for combustion that combines DMC and DC (Van Wagner, 1987).

Cellular automata (CA) for fire growth modelling: A grid cell based process that sends out firelets one at a time from the fire source. The initial firelet (ignition) survives by ignites new fuel and moves in the direction determined by the fire environment (e.g. fuels, weather) (Clarke et al., 1994).

Crown Fires: Crown fires burn the crowns (tops) of trees or shrubs (Fuller, 1991). During intermittent crown fires, the fire switches between crown and surface fire behaviour.

Distance Threshold: Prometheus allows the user to define a distance threshold (measured in grid cells). The default distance threshold is set at 1.00, which is equivalent to the fuel grid resolution. The distance threshold is the maximum distance allowed between any two adjacent vertices on a fire perimeter before the point insertion technique is executed. More vertices will be added along a given fire perimeter as the user decreases the distance threshold value. This results in a smoother elliptical perimeter. However, adding more vertices increases the number of calculations and reduces the overall speed of the model.

e.g.) the distance threshold is set at 1.00 and the fuel grid resolution is 25 meters. New vertices will be added at the end of a given time step wherever the distance between neighbouring vertices is 25 meters or greater (McLoughlin, 2007).

Drought Code (DC): A numerical rating of the average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels, and amount smoldering in deep duff layers and large logs (Van Wagner, 1987).

Duff Moisture Code (DMC): A numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. The code gives an indication of fuel consumption in moderate duff layers and medium-size woody material (Van Wagner, 1987).

Ecological Risk: The risk of loss of fire dependent species and vegetation communities. Measured indirectly by comparing the current fire cycle with the long-term fire cycle as measured through fire history studies. An assumption is made that the closer the current fire cycle is to the long-term fire cycle the less risk there is of loss of fire dependent species and communities (Anonymous, 2007).

Ecosystem Resilience: The ability of an ecosystem to recover from disturbances caused by natural and human-induced means. It may be measured as the magnitude of disturbance that can be absorbed before the ecosystem changes its structure by changing the variables and processes that control behaviour. It can also be described as the measure of resistance to disturbance and speed of return to the ecosystem's equilibrium state.

Extreme or Catastrophic Wildfire Events: These events are typically characterized by extremely high drought and high fine fuel moisture codes, thus contributing to uncontrollable fire behaviour conditions. Wildfires in this category are likely to escape tactical fire suppression efforts and therefore potentially threaten values at risk. There are often significant economic implications of such fires in the wildland urban interfaces.

Fine Fuel Moisture Code (FFMC): A numerical rating of the moisture content of litter and other cured fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel (Van Wagner, 1987).

Fire Cycle: The number of years required to burn over an area equal to the entire area of interest (Anonymous, 2003).

Fire Interval: The average number of years between the occurrences of fires at a given point (Anonymous, 2003).

Fire Regime: The kind of fire activity or pattern of fires that generally characterize a given area (Anonymous, 2003). A fire regime is the combination of a fire history (fire behaviour and occurrence) and a certain complex of fuel (biota) (Pyne, 1984). It is dependent on the rate of spread, shape, intensity, frequency (time between fires), season of burning, the extent (patchiness), type of fire (fire behaviour), fuel source and moisture level, weather, and ignition source (McLoughlin, 1998; Pyne, 1984; Whelan, 1995). Some important elements of the characteristic pattern include fire cycle or fire interval, fire season, and the number, type, and intensity of fires (Anonymous, 2003).

Fire Season: The period(s) of the year during which fires are likely to start, spread, and do damage to values -at-risk sufficient to warrant organized fire suppression; a period of the year set out and commonly referred to in fire prevention legislation. The fire season is usually further divided on the basis of the seasonal flammability of fuel types (e.g. spring, summer, and fall) (Anonymous, 2003).

Fire Severity: A general term most commonly describe the combined affects of both flaming combustion and smouldering combustion on either a wildfire or prescribed fire site as manifested in various fire behaviour characteristics (e.g. fire intensity, flame height and length, residence and burn-out times, etc.); this is quite inferred after-the fact from the fire impact(s) (Anonymous, 2003).

Fire Weather Index (FWI): A numerical rating of fire intensity that combines ISI and BUI. It is suitable as a general index of fire danger throughout the forested areas of Canada (Van Wagner, 1987).

Fuel Hazards: The amount and condition of fuels available for combustion.

Ground Fires: This fire type burns the duff and organic material in the soil beneath the surface litter. They are typically slow moving fires that are difficult to fully extinguish.

Initial Spread Index (ISI): A numerical rating of the expected rate of fire spread. It combines the effects of wind and FMC on rate of spread without the influence of variable quantities of fuel (Van Wagner, 1987).

Interface Fires: Fires within the wildland urban interface (Partners in Protection, 2003).

Pyrodiversity: (the variety in intervals between fires, seasonality, and fire characteristics at various scales) (Graham et al., 2004; Stephens, 1998)

Raster versus Vector Data Formats: A raster data format consists of a grid of cells in which each pixel represents one unique value. Raster data is commonly found in remotely sensed images or representing a continuous surface of information. A vector data format consists of points, lines, or polygons that are made up from individual or combination Cartesian coordinates. The advantage of vector data is many attributes can be associated with them, while raster data represents one value per pixel.

Random versus Strategic Fuel Treatments: For the purpose of this research, *random* fuel treatments are those treatments that are have not been strategically designed and are therefore scattered across the landscape. Treatments are randomly chosen from a subset of targeted flammable fuels and are therefore not truly random (i.e. they are not chosen randomly from all fuels in the landscape). *Strategic* fuel treatments are those treatments that are designed as large barriers to fire spread, such as bulkhead firebreaks. These treatments are currently used by most fire management agencies in Canada.

Seasonal Severity Index: The seasonal severity index is used to represent the severity of the fire season, as an accumulation of all the fire weather that has occurred during a fire season.

Surface Fires: Surface fires burn the fine fuels such as the surface litter, grasses, forbs and shrubs. They do not burn into the crown (tops of trees) nor burn into the duff and organic material beneath the surface litter.

Values at Risk: The specific or collective set of natural resources and human made improvements/developments that have measurable or intrinsic worth and that could or may be destroyed or other wise altered by fire in any give area (Anonymous, 2007).

Wavelet Resolution Settings: Wavelet (Vertex) Resolution Settings control how **new** vertices are added to a fire perimeter in the *Prometheus* fire growth model. Angle and distance thresholds are used to specify the models Wavelet Resolution Settings. The point insertion technique is used to add new vertices to a fire front. New vertices are only added along the **active** portion of a fire front. New vertices are added at a mid-point between existing vertices when threshold conditions are appropriate. The point insertion technique is an iterative routine that can introduce a maximum of five new vertices every time a threshold condition is detected. This limitation is imposed to avoid an unreasonably large number of vertices from being introduced at any given time step (which would otherwise happen at extremely sharp turns along the fire front). However, there is no upper limit to the number of vertices that the **entire** fire perimeter can contain (McLoughlin, 2007).

Wildfire Risk: The risk of wildfire negatively affecting human safety, infrastructure, ecological and cultural resources (Values at Risk). Wildfire risk can be mitigated in three ways, by having sufficient fire suppression resources to extinguish all wildfires, by limiting the spread of wildfires towards values at risk with strategic prescribed fires, and by limiting the spread of fire towards values at risk through fuel management (Anonymous, 2007).

Wildland urban interface: can be defined as any area where industrial, agricultural, or recreational developments or homes are intermixed with flammable natural vegetation (Partners in Protection, 2003).

Appendix B

Sample Pandora Parameters File

		Explanation of Parameters
NumberofRuns	75	# of simulations in this batch file
BatchRun#	1	The simulation number
Fire_Name	Quetico_scen13_50m	Name of final file for the simulation
Projection_File	C:\batch\Projection.prj	Projection File location
FBP_GridFile	C:\batch\scen13.asc	FBP Fuels grid ASCII location
Elev_GridFile	None	Elevation file location
Slope_GridFile	None	Slope file location
Aspect_GridFile none	None	Aspect file location
WxStation_Lat	48.6999	Latitude of weather station used
WxStation_Lon	-91.4779	Longitude of weather station used
WxStation_Elev	389.3	Elevation of weather station used in m
Wx_File	C:\batch\ws_July7_2001_NEW	Weather file location
Init_FFMC	80.1	Initial FFMC value used
Init_DMC	18	Initial DMC value used
Init_DC	178	Initial DC value used
Init_hour	0	Initial hour in the weather file
FFMC_Method	0	Van Wagner vs Lawson Hourly wx
Grass_curing%	90	% of grass curing used in fire engine
Ign_DateTime	07/07/2001:02:00:00	Ignition date and time
Ign_X	256	Ignition X coordinate
Ign_Y	687	Ignition Y coordinate
Fuel_Table	None	Location of fuel lookup table
Angle_Distance	5 2	Angle (°) and Distance (grid cells) thresholds
Option1	None	Program line for future options
Option2	None	Program line for future options
Option3	None	Program line for future options
Time_Interval	180	Time between each fire front calc (sec)
Time_Steps	87	# of hours in weather stream
Out_Perimeters	0	# of fire perimeters (.shp) to be exported
Out_ShapeFiles	C:\batch\Output\ws6_19scen1	Location and name for exported file
Out_GridFiles	None	# of grids to be exported (.asc)
Out_Components	None	Identify other parameters to output
End_Batch	999	End of the simulation run in the batch file

Appendix C

16 benchmark fuel types of the Fire Behaviour Predication (FBP) System. Bolded fuel types were used in this research.

Fuel Type	Fuel Type Description
C-1: Spruce-lichen Woodland	Open, park-like black spruce stands in well-drained uplands in the subarctic zone of western and northern Canada. Forest cover occurs as widely spaced individuals and dense clumps. Tree heights vary considerably, but bole braches extend to the forest floor and layering development is extensive. Light and scattered accumulation of woody surface fuel. Shrub cover is exceedingly sparse. The ground surface is fully exposed to the sun and covered by a nearly continuous mat of reindeer lichens, averaging 3-4 cm in depth above mineral soil.
C-2: Boreal Spruce	Pure, moderately well-stocked black spruce stands on lowland (excluding *Sphagnum* bogs) and upland sites. Tree crowns extend to or near the ground, and dead branches are typically draped with bearded lichens. Low to moderate volumes of down woody material, with Labrador tea the major shrub component. The forest floor is dominated by feather mosses and/or ground-dwelling lichens. A compacted organic layer commonly exceeds a depth of 20–30 cm.
C-3: Mature Jack or Lodgepole Pin	Pure, fully stocked (1000–2000 stems/ha) jack pine or lodgepole pine stands, matured with complete crown closure. The base of live crown is well above the ground. Dead surface fuels are light and scattered. Ground cover is feather moss over a moderately deep (approximately 10 cm), compacted organic layer. A sparse conifer understory may be present.
C-4: Immature Jack or Lodgepole Pine	Pure, dense jack pine or lodgepole pine stands (10 000–30 000 stems/ha) with natural thinning mortality resulting in large quantity of standing dead stems and dead downed woody fuel. Vertical and horizontal fuel continuity, with surface fuel loadings greater than in fuel type C3, and organic layers are shallower and less compact. Ground cover is mainly needle litter suspended within a low shrub layer.

C-5: Red and White Pine	Mature stands of red pine and eastern white pine in various proportions, with small components of white spruce and old white birch or aspen. Moderate understorey red maple or balsam fir. Shrub layer, usually beaked hazelnut, may be present in moderate proportions. The ground surface cover is a combination of herbs and pine litter. The organic layer is usually 5–10 cm deep.
C-6: Conifer Plantation	Pure, fully stocked conifer plantations with closed crowns and no understory or shrub layer. The forest floor is covered by needle litter with an underlying duff layer up to 10 cm deep. The crown base height is taken into account in predicting fire spread rate and crowning.
C-7: Ponderosa Pine and Douglas Fir	Uneven-aged stands of ponderosa pine and Douglas-fir in various proportions. Western larch and lodgepole pine may be significant stand components on some sites and at some elevations. Stands are open, with occasional clumpy thickets of multiaged Douglas-fir and/or larch as a discontinuous understory. Canopy closure is less than 50% overall, although thickets are closed and often dense. Woody surface fuel accumulations are light and scattered. Except within Douglas-fir thickets, the forest floor is dominated by perennial grasses, herbs, and scattered shrubs. Within tree thickets, needle litter is the predominant surface fuel. Duff layers are nonexistent to shallow (<3 cm).
D-1: Leafless Aspen	Pure, semimature 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.
S-1: Jack or Lodgepole Pine Slash	Sslash resulting from tractor or skidder clear-cut logging of mature jack pine or lodgepole pine stands. Typically one or two seasons old, retaining up to 50% of the foliage, particularly on branches closest to the ground. No postlogging treatment, and slash fuels are continuous. Tops and branches left on site result in moderate fuel loads and depths. Ground cover is continuous feather moss mixed

	with discontinuous fallen needle litter. Organic layers are moderately deep and fairly compact.
S-2: White Spruce-Balsam Slash	Slash resulting from tractor or skidder clear-cut logging of mature to overmature stands of white spruce and alpine fir or balsam fir. Typically one or two seasons old, retaining from 10% to 50% of foliage on the branches. No postlogging treatment. Fuel continuity may be broken by skid trails unless the site was logged in winter. Tops have been left on site, and most branch fuels have broken off during skidding of logs to landings, which results in moderate fuel loads and depths. Quantities of shattered large and rotten woody fuels may be significant. Ground cover is feather moss with considerable needle litter fallen from the slash. Organic layers are moderately deep and compact.
S-3: Coastal Cedar-Hemlock-Douglas Fir Slash	Slash resulting from high-lead clear-cut logging of mature to overmature coastal British Columbia mixed conifer stands. Predominant species are western red cedar, western hemlock, and Douglas-fir. Typically one season old, with the cedar component retaining all its foliage in a cured condition on the branches, whereas the hemlock and Douglas-fir components will have dropped up to 50% of their foliage. Slash fuels tend to be continuous and uncompacted. Very large loadings of broken and rotten unmerchantable material may be present, depending on degree of stand decadence. Slash fuel depths may range from 0.5 to 2.0 m. Ground cover of feather moss or compact old needle litter under significant quantities of recent needle litter fallen from the slash. Organic layers are moderately deep to deep and compact. Minor to moderate shrub and herbaceous understory components may be present. This fuel type designation may also be applied to wet belt cedar–hemlock slash of coastal and interior British Columbia where the Douglas-fir component is absent.
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-1: Boreal Mixedwood Leafless	This fuel type (and its "green" counterpart, M2) is characterized by stand mixtures consisting of the following coniferous and deciduous tree species in varying proportions: black spruce, white spruce, balsam fir, subalpine fir, trembling aspen and white birch. On any specific site, individual species can be present or absent from the mixture. In addition to the diversity in species composition, stands exhibit wide variability in structure and development, but are generally confined to moderately well-drained upland sites. M1, the first phase of seasonal variation in flammability, occurs during the spring and fall. The rate of spread is weighted according to the proportion (expressed as a percentage) of softwood and hardwood components.
M-2: Boreal Mixedwood-Green	M2, 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.
M-3: Dead Balsam Fir Mixedwood-Leafless	This fuel type (and its "green" counterpart, M4) is characterized by mixedwood stands in which balsam fir grows, often as an understory species, in a heterogeneous mix with spruce, pine, and birch. These stands are found in the Great Lakes – St. Lawrence and Boreal Forest regions of Canada and are not to be confused with the pure balsam fir stands typical of Nova Scotia and New Brunswick. Repeated annual defoliation (due to spruce budworm attack) causes balsam fir mortality, followed by peeling bark, draped lichen development, top breakage, and windthrow, peaking 5–8 years after mortality. The volume of down woody material is initially low but increases substantially with progressive stand decomposition following mortality. The forest floor is a mixture of feather mosses, conifer needles, and hardwood leaves. The organic layer is moderately compacted and 8–10 cm deep. After mortality, spring fires in this fuel type behave extremely vigorously, with continuous crowning and downwind spotting. The rate of spread is weighted according to the

	proportion (expressed as a percentage) of dead fir present on the site (pdf).
M-4: Dead Balsam Fir Mixedwood-Green	Leafed Counterpart to M-3.
	Source: Canadian Forest Service, 2007.