Modelling Fire Cessation in the Canadian Rocky Mountains

by

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Abstract

In many regions of the world, fires are the primary environmental disturbance producing a mosaic of burned and unburned patches varying at temporal and spatial scales and providing a variety of ecosystem services. Fire perimeters mark the separation between the burned and unburned matrix of a fire. In prior studies in the United States, Australia, and Alberta, variations in the fire environment, fuel, weather, topography, and anthropogenic factors, affected fire perimeter formation. One of the critical challenges in interpreting and comparing regional variations in the fire cessation process is that each study employs a different sample distance and analysis technique.

In this study, I examined fire cessation in the western Canadian Rocky Mountain region, where no fire extinguishment studies have been undertaken despite human values at risk facing increased fire hazards. This study investigates how fire environment factors influence fire cessation on the 2017 Verdant Creek Fire in Kootenay National Park. The Verdant Creek Fire is ideally suited to this research as it burned under a variety of environmental conditions, with a varying application of suppression techniques. This work evaluated the performance of 16 distances of analysis for comparing exterior unburned areas with interior burned areas to identify how static variables influence fire cessation. Two spatial and temporal scales assessed the influence of weather on fire boundary formation. The potential influence of fire suppression on fire cessation was also examined. Data were extracted using GIS and analyzed with statistical modelling using matched case-control conditional logistic regression. Predictive fire boundary models were compared to determine the effectiveness of different distances of analysis and predictor variables.

Results indicated that fire boundary formation was strongly influenced by fuel composition, arrangement, and to a limited extent, topography. Weather influenced fire boundary formation, but mainly in areas where suppression occurred. Suppression was successful in periods of diminished weather conditions, and areas near waterways. The influence of vegetation was largely consistent regardless of the implementation of suppression tactics. While results from the weather model have applications in operational fire management, occurring over a limited period (1–14 days), the stable fire environment model has applications in strategic planning as it uses variables that are relatively consistent over extended periods (1–5 years). Results from the best sample distance were used to develop a Spread Potential Index (SPI). The SPI was used to map the probability of fire spread. The SPI has potential uses in strategic fire management activities as a tool for rapid visual assessment on the influence of temporally stable fire environmental factors on fire cessation.

Lightning slaps at timberline on Mount Verendrye
Sparks dance in the evening, exploding in the heat of day
See flames on a ridgetop, ancient timber set ablaze
Driest spell in 100 years, no rain for 40 days
And the winds fan her northward, up Vermillion Pass
Firefighters muster, to a monumental task
Blinded by the smoke and ash, they fight to hold their ground
Back up boys, she's hot as hell; this devil wears a crown

4000 acres smoulder in her wake
Chainsaws and D-9 cats carve a firebreak
Gotta stop this wildfire boys, before it's too late

Valley, the Bow Valley
Lies in her path
Valley beautiful valley
She'll be turning to ash

The second strike up Tokumn Creek, the fire begins to spread
Fires unite in a wall of flame, embers leap ahead
Choppers work the hotspots; sprinklers hold the line
Backfire meets the roaring heat in the nick of time

Heres to unsung heroes, saved the town that day
Hadn't stopped her on the Great Divide, would have got away
Wind blows down the Kootenay, the thunder roars
Heat will come, lightning strikes, fire will take its toll

4000 acres smoulder in her wake
Chainsaws and D-9 cats carve a firebreak
Gotta stop this wildfire boys, before it's too late
Gotta stop this wildfire boys, before it's too late

- The Wardens, Backfire

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

BEC – Biogeoclimatic Ecosystem Classification

BUI – Build-up Index

DC – Drought Code

DEM – Digital Elevation Model

DMC – Duff Moisture Code

ESSF – Engelman spruce – subalpine fir

FBP System – Fire Behaviour Prediction System

C-2 – FBP System fuel type for Boreal Spruce

C-3 – FBP System fuel type for Mature Jack of Lodgepole Pine

C-7 – FBP System fuel type for Ponderosa Pine – Douglas Fir

D-1 – FBP System fuel type for Leafless Aspen

M-1/M-2 – FBP System fuel types for Leafless/Green Boreal Mixed Wood

O-1 a/b – FBP System fuel types for Matted/Standing Grass

FFMC – Fine Fuel Moisture Code

FWI – Fire Weather Index

GPS – Global Positioning System

HLI – Heat Load Index

IMA – Interior Mountain Heather Alpine

ISI – Initial Spread Index

KNP – Kootenay National Park

MAPP – Mount Assiniboine Provincial Park

MS – Montane Spruce

SPI – Spread Potential Index

TCI – Topographic Convergence Index

TPI – Topographic Position Index

TWI – Topographic Wetness Index

WDSP - Windspeed

Chapter 1 Introduction

1.1 Project Overview

Lightning strikes and a fire starts in the Canadian Rocky Mountains. The fire licks at mosses and twigs, dried from a season without rain. As the kindling understory pulses with energy, the fire grabs at low hanging branches and swings upwards. With enough vegetation aflame below, the fire erupts into the forest canopy, hungrily consuming sun-baked needle tips. Winds unhindered by treetops propel the fire forward. Steep mountainsides allow the bending flames to preheat the fuels, and the fire spreads rapidly upslope. The fire becomes a bubbling mass on the landscape, an unstoppable conflagration, consuming everything in its path. Yet, at some point, the fire stops. There is an edge. A fire perimeter.

This fire perimeter represents the actualization of several processes that contribute to fire cessation. As long as a mapped fire perimeter exists alongside characteristics of the fire environment, including fuels, weather, topography, and anthropogenic factors, one can investigate and attempt to understand why the fire stopped. An understanding of fire perimeter formation will assist agencies across Canada who aim to manage fire disturbance for ecological and financial benefits. These agencies face the challenge of letting fires burn in a manner that does not put people or values at an unacceptable risk. To allow fire on the landscape, managers need tools to predict the locations and conditions that have a good chance of arresting fire spread and containing the fire. Studies in the United States, Australia, and Alberta have examined the relationship between the fire environment and fire perimeter formation. Yet no studies to date have addressed the fire cessation processes in the western Canadian Rocky Mountains.

1.2 Context

Humans have influenced fire regimes across Canadian landscapes for thousands of years. Fire was first harnessed by Indigenous peoples, who developed and employed fire knowledge to meet land management objectives, including agro-ecology, fuel modification, travel, and cultural purposes (Lewis and Ferguson 1988; Huffman 2013). When settlers arrived in North America, they ignited fires to clear land, occasionally resulting in conflagrations with catastrophic losses, such as the 1916 Matheson fire that caused over 200 fatalities (Southall 1991; Alexander and Taylor 2010). As forestry became a dominant Canadian industry in the late 19th century, timber values and the forests that contained them required protection from the destructive force of fire. Land managers enacted fire suppression policies in response to the desire to protect people, property, and resources (Pyne 2007). Suppression focused on the extinguishment of fire below pre-determined sizes and within specified time thresholds (Cumming 2001; North et al. 2015). To meet these demands and ensure effective preparedness planning and fire suppression response, researchers developed fire management information tools to support fire managers' decisions (Van Wagner 1990; Lee et al. 2003) most notably, the Canadian Forest Fire Danger Rating System (CFFDRS)(Stocks et al. 1989) and its two subsystems: the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). These tools allowed fire managers to assess fire danger across time and space and position resources in optimal locations to achieve fire suppression objectives.

By the 1970s, fire management agencies in Canada were exceedingly effective at using fire suppression to stop forest fires, but their success generated unintended consequences (Simard 1976). Suppression is thought to contribute to a long-term feedback loop by increasing forest homogeneity and predisposing the forest to ignitions and burning (Erni et al. 2018). These factors may enable a landscape to support fires at intensities (energy released) and severities (stand mortality) beyond historical ranges of variability (Schoennagel et al. 2004; Stephens and Ruth 2005). Furthermore, in some ecosystems, increasing the time elapsed since fire has been shown to increase the likelihood that fire will escape initial suppression efforts (Beverly 2017). In Canada and the United States, failure of initial containment occurs only 3% of the time often under extreme weather conditions, but these escaped fires are responsible for 85-98% of the area burned (Stocks et al. 2002; Donovan and Brown 2005; Quince 2009) and are responsible for the majority of fire management expenditures (Katuwal et al. 2016). Increasing fire occurrence and intensities increase demands on resources required to achieve suppression objectives, further increasing costs (Kiil 1979; Stocks and Martell 2016). Fire exclusion through suppression action is increasingly viewed as an expensive and unsustainable fire management objective, that is unattainable under extreme fire environment conditions (Busenberg 2004; Dunn et al. 2017a, 2017b).

In an effort to modernize the economics of fire, agencies began to seek management alternatives, policy reforms, and in turn, the fire science required to inform change. An understanding that fire was a natural part of many forest ecosystems was explored in the early 20th century (Whitford 1901), but with increased intensity and interest from the 1950s onwards (Leopold et al. 1963; Wright and Bailey 1982). Agencies developed policies that enabled the use of prescribed burning to achieve management objectives (Weber and Taylor 1992), and appropriate response to fires (Canadian Council of Forest Ministers 2005; Martell 2015). A new suite of tools was required to meet these new policy demands. Management of fire as part of the landscape was accompanied by a need to protect communities and values at risk from fire. New approaches were developed to assess and mitigate risks through community protection planning using approaches such as fire threat rating (Hawkes and Beck 1997), FireSmart landscapes (Hirschl et al. 2001), and ignition exposure assessments (Beverly et al. 2010). To protect values at risk, managers needed to know where fires were likely to occur and spread over time and space. In response, researchers developed modelling systems: CanFIRE (Groot et al. 2002), Burn-P3 (Parisien et al. 2005), Prometheus (Tymstra et al. 2010) and the Probabilistic Fire Management System (PFAS) (Natural Resources Canada 2011). These systems allowed managers to simulate fire growth, and evaluate potential containment lines to minimize fire spread and protect values at risk (Anderson 1989; Fried and Fried 1996; Donovan and Rideout 2003; Finney 2004; Hu et al. 2009).

Yet, these models draw from the original fire management toolbox focusing on fire initiation and propagation. Research into fire cessation began with investigations of weather ending events to support go/no-go decisions for let-burn fires (Latham and Rothermel 1993; McIntire 2004; Calkin et al. 2011; Wang et al. 2014), to detect weather conditions leading to large fire growth (Beverly and Martell 2005; Podur and Wotton 2011), and by devising modelling for minimum fuel break distances required to stop fires spreading under a given set of fire environment factors (Alexander et al. 2004). These approaches generally neglected to account for complex fire environment interactions that accompany fire cessation (Holsinger et al. 2016). Models cannot realistically simulate actual fire growth if they cannot adequately predict the locations and conditions likely to produce fire cessation. An emerging focal area of fire research seeks to understand the process of fire cessation and develop tools to help managers identify locations most likely to slow fire spread and form boundaries. This information can be expected to result in improved decisions that reduce risk to wildland firefighters and public safety while limiting resource use and costs. This thesis investigates fire cessation for a case study fire in the Canadian Rocky Mountains using spatial statistical modelling methods to explore the influence of the fire environment, weather, topography, vegetation, and anthropogenic factors, on fire perimeter formation at multiple distances of analysis.

1.3 Fire Boundary Formation and the Fire Environment

Like fire growth, the process of fire cessation occurs in relationship to the fire environment. At the smallest scale, combustion is a process dependent on the presence of adequate quantities of fuel, oxygen, in addition to a heat source. Removing any one of these three inputs to the fire equation will halt the combustion process. At larger spatial scales, fires are affected by the fire environment, topography, weather, fuels and anthropogenic influence on the fuels (Countryman 1972). For a fire to ignite, all factors of the fire environment must be conducive to fire spread (Bradstock 2010). Once spread is achieved, the fire environment will continue to influence propagation and eventual extinguishment (Rothermel 1983) until intensity drops below 100 kW m^{-1} and fire extinguishment occurs (Price et al. 2014). When fires stop, they produce fire boundaries and fire refugia, representing the division between the burned and unburned landcover matrix. Fire perimeters and refugia are routinely mapped as part of agency fire management operations, which makes it possible to study the influence of the fire environment on fire cessation. The following sections provide an overview of how regional fire environment variations can be expected to interact with the process of fire cessation.

1.3.1 Topography

Topography describes the character of the landscape, including slope, aspect, and terrain (Swanson 1981), which affect fire propagation and cessation. Topography is the most temporally consistent aspect of the fire environment, acting as a bottom-up influencer, or template, upon which local weather, vegetation patterns, and fire behaviour occur (Turner 2005). Elevation, in combination with climate, can produce steep biophysical gradients affecting the distribution and arrangement of fuels (Meidinger and Pojar 1991; Krawchuk et al. 2016). Easily identifiable fire breaks occur where elevation and the resulting biophysical gradients limit the spatial distribution of fuels and, in turn, fire spread (Kasischke et al. 2002; Harris and Taylor 2017). In the Canadian Shield of Saskatchewan, higher elevation areas are limited to height of land ridges or knolls where the hot and dry climate is enhanced, increasing fire weather and severity in these elevated areas; however, in the Foothills of Alberta, the overall climate is cold and wet, such that increased elevation limits vegetation and in turn, fire severity (Ferster et al. 2016). Holsinger et al. (2016) used the

Topographic Position Index (TPI) (Conrad et al. 2015), to detect fire boundary formation in relation to ridges and valleys in the western United States. Similarly, the ruggedness of complex terrain may produce firebreaks at ridges, talus slopes, avalanche paths, and large water bodies as observed across the United States (Swanson 1981; Iniguez et al. 2008). Steep slopes can propagate fire by pre-heating fuels as the fire moves upslope, but if a slope is too steep, it will be unable to hold moisture resulting in sparse fuels that slow fire spread (Taylor and Skinner 2003; Beaty and Taylor 2008; Ferster et al. 2016). When the terrain is flat, topography is easily overridden by weather unless depressions enable the formation of wetlands, water bodies, or rivers that, in turn, serve as firebreaks (Hirsch and Fuglem 2006).

Topography can produce inconspicuous conditions that limit fire propagation. In the Rocky Mountains of British Columbia, fire refugia persist through multiple fire events in concave catchment basins with moderate slopes (Krawchuk et al. 2016). The correlation between fire perimeter locations and valley bottoms indicates a temperature and moisture relationship whereby cold air and moisture pools in valleys because of downslope winds (Narayanaraj and Wimberly 2011). In the Foothill region of Alberta, areas outside the fire perimeter had higher soil moisture than the interior of the perimeter, including refugia (Andison 2012). Krawchuk et al. (2016), employed the Topographic Wetness Index (TWI) and Topographic Convergence Index (TCI), to explore how the catchment area of surrounding slopes influenced the potential for soil water and cold air pooling, and resulting fire cessation (Böhner and Selige 2006; Conrad et al. 2015).

Aspect affects a site's incoming solar radiation, altering the Heat Load Index (HLI) and, thus, vegetation patterns (McCune and Keon 2002). In the northern hemisphere, slopes with dry and warm southerly aspects are more likely to burn than cool and wet northerly aspects that have a lower HLI (Heyerdahl et al. 2001; Bigio et al. 2016). Under extreme drought conditions, northern slopes can dry out, providing fire access to an otherwise moist and heavy fuel landscape that can now burn at high fire intensity and severity (Wimberly and Reilly 2007). Topography can produce observable firebreaks and discrete areas with lower receptivity to ignition unless under extenuating conditions.

Topography exerts a complex influence on fire cessation, with regional and localized interactions dependent on other elements of the fire environment that combine to influence fire cessation. Further research is required to characterize the influence of topography on fire cessation at multiple scales.

1.3.2 Weather

Weather is the atmospheric conditions at a given place and time, usually described by wind speed and direction, relative humidity, temperature, precipitation, and atmospheric stability. Weather is the most dynamic and complex aspect of the fire environment, varying over temporal scales of decades to minutes (Heyerdahl et al. 2001) and spatial scales of kilometres to centimetres (Hilton et al. 2015). Climate is the prevailing weather conditions for a given period and location.

Topography has a bottom-up influence on local fire weather and resulting fire behaviour, whereas climate and extreme weather have top-down effects on fire behaviour. Bottom-up contributions of local terrain produce regional weather variations, such as differences in precipitation, heat indices, evapotranspiration, surface winds, cold air pooling, and thermal belts (Kolden et al. 2017). In Mediterranean ecoregions of California Coppoletta et al. (2016), observed that high severity fires were consistently associated with low relative humidity and high temperatures. Rough mountainous terrain can produce thermal belts, or pockets of warm nighttime air, allowing a fire to burn throughout the night. Rugged terrain in Japan and New Mexico creates pockets of cold air in valley bottoms, enhancing fuel moisture contents and, in turn, limiting burning (Yoshino 1984; Haire et al. 2017).

Under extreme weather conditions, the protective effects of topography on fire behaviour diminish (Cansler and Mckenzie 2014). Across the American Rocky Mountains, studies have shown that even formidable topographic obstacles had little influence on fire spread or behaviour due to heightened drying of all fuels and susceptibility to ignitions from spot fires (Schoennagel et al. 2004). Likewise, in areas with flatter terrain, the effects of topography are limited and easily overridden by weather (Cansler and Mckenzie 2014). In the southwestern United States under extreme weather conditions, fuels ordinarily unavailable for combustion due to high moisture contents begin to dry, contributing to high fire intensities and burn severities (Iniguez et al. 2008; Kane et al. 2015; Harris and Taylor 2017). In the Canadian west, similar prolonged drying conditions allow fire to consume normally unavailable fuels and even persistent fire refugia (Ferster et al. 2016; Krawchuk et al. 2016).

Extended climatic extremes may alter a site's productivity or fire regime (Parks et al. 2018). This effect is evident when comparing the duration of a fire's protective effects against subsequent fire, shown to persist up to 30 years in wet and cold northern ecosystems of the United States, in comparison with only 15 years in the dry, warm southern ecosystems (Parks et al. 2016). Similarly, in the Canadian boreal, fire growth in previously disturbed and now regenerating areas is reduced unless enhanced by drought (Amiro et al. 2004; Beverly 2017). In the southern Rockies of the United States, refugia persisted through multiple fire events, until an extreme drought significantly reduced fuel moisture, enabling refugia to burn (Haire et al. 2017). As a result of the overriding effects of weather, control lines placed in intuitive topographic locations are prone to failure during extreme weather events (Swanson 1981; Narayanaraj and Wimberly 2011). Extreme weather, over short and extended periods, influences fire growth by overriding barriers that would limit fire spread under normal conditions.

The moisture content of vegetation is directly related to local temperature and atmospheric moisture and influences vegetation susceptibility to fire (Schroeder and Buck 1970). Vapour Pressure Deficit (VPD), measures the difference between the saturation vapour pressure and the vapour pressure of an air mass, accounting for the difference between temperature and relative humidity (Lawrence 2005). A higher VPD indicates desiccating atmospheric conditions that decrease a plant's moisture content values and increase vegetation susceptibility to initial ignition and fire spread (Sedano and Randerson 2014; Seager et al. 2015). In the Nebraska Sandhills, lower VPD values associate with fire cessation (Just et al. 2016).

The Canadian FWI system tracks the influence of weather on daily fuel moisture conditions (Van Wagner 1987). The Fine Fuel Moisture Code (FFMC) tracks moisture in litter and other fine fuels and is considered an indicator of the ease of ignition (Beverly and Wotton 2007). The Duff Moisture Code (DMC) tracks moisture in loosely compacted organic layers and medium-sized fuels, and is considered an indicator of potential fuel consumption (Van Wagner 1977). The Drought Code (DC) tracks moisture content in deep duff layers and large fuels and is considered an indicator of seasonal drought (Van Wagner 1977). The drying time lag required for FWI system codes to reach equilibrium moisture content with the surrounding environment is 2/3 of a day, 15, and 53 days for FFMC, DMC, and DC, respectively (Van Wagner 1987). The moisture codes are used to derive equivalencies to Byram's equation parameters for fireline intensity (Equation 1). The output, I, is the energy per unit length of fire front, for the input parameters, H is the heat of combustion, W is the weight of fuel consumed for an area, and R is the rate of spread, using compatible units (Byram 1959).

$$I = HWR$$

Equation 1: Fireline intensity (Byram 1959)

The Initial Spread Index (ISI) provides a relative rating of the rate of fire spread based on the FFMC and wind speed; the Build-up Index (BUI) combines DMC and DC to indicate the amount of fuel available for consumption, and the FWI combines the BUI and ISI to provide an indicator of fireline intensity (Van Wagner 1987). In Ontario, Podur and Wotton (2011) found the FWI system was suitable for predicting days when the fire was actively growing and spreading, termed "spread-event" days, but was not significant for predicting non-spread event days.

Research to date on fire cessation indicates that although weather may limit fire spread, fuel and topography are more influential for extinguishment. In Australia, weather influenced fire growth but only had minor significance for predicting fire perimeter formation (Price et al. 2014). In the rugged terrain of the southern United States, fuel distribution, rather than weather, was also found to drive fire cessation (Holsinger et al. 2016). Similarly, Krawchuk et al. (2006) found that in the Canadian boreal forest, ignition probability was dependent on fuels present and not on weather conditions. In contrast, temperature was the most significant contributor to the process of fire cessation in the Northern Rockies of the United States (Holsinger et al. 2016). The nature of interactions among fire environment factors appears to depend on the strength of the relationship between the bottom-up and top-down influences in a given ecosystem, such that the importance of extreme weather is observable but has varying influences across ecoregions.

Climate change heightens the need to determine how weather influences fire cessation. Climate change is expected to increase the intensity and occurrence of fire events (Flannigan et al. 2005; Wotton et al. 2010), by altering weather patterns (Flannigan et al. 2016). Krawchuk et al. (2016), hypothesize that under climate change, extreme weather conditions may override current relationships between top-down and bottom-up influences. As severe weather becomes more frequent, fire suppression tactics may fail at a higher rate (Beverly 2017). Climate change extremes could elevate the importance of weather to fire cessation relative to the influence of fuels or topography; however, without an understanding of the current relationship, it will be difficult to assess changes over time.

Few fire cessation studies have attempted to understand the exact influence of weather on fire cessation due to weather's high temporal and spatial variability. Ferster et al. (2016) assessed the influence of weather on fire severity but were unable to evaluate the influence on perimeter formation due to weather variability. Narayanaraj and Wimberly (2011), Andison (2012), and Povak et al. (2018) excluded weather from analyses in favour of the static topographic and vegetational influences on fire cessation. O'Connor et al. (2017) proposed that by using a large number of fires (238), which had presumably stopped under a range of weather conditions, weather became a background signal allowing for the emergence of vegetation and topographic influences on fire cessation. Price et al. (2014) incorporated weather using stations distant from the fires (12 to 112 km), potentially resulting in the low correlations between weather and fire cessation. Likewise, Holsinger et al. (2016) associated daily weather variables using nearby stations; however, they incorporated the potential effects of diminishing fire weather on fire cessation by assigning daily values one day after the estimated date of burning for boundary locations. They observed that weather was influential to fire cessation in the northwestern United States but was less prominent in the southwestern United States. The incorporation of weather into fire cessation studies is currently limited to broad temporal and spatial scales due to the difficulty of relating available weather to a given point in space and time, which is typically accomplished by using satellite data to detect the date of burning for a location.

Weather is a dynamic aspect of the fire environment and presents an equally complicated relationship with fire cessation. The weather appears to have regional and localized interaction with other elements of the fire environment that combine to influence fire cessation. At some distances from the fire perimeter, weather and climate may have limited influence on fire cessation; due to factors such as fine-scale weather variations at the site of the fire that are not captured by weather data from nearby stations. More research is required to understand the influence of weather on fire cessation over multiple distances of analysis and temporal scales.

1.3.3 Fuel

Fuel has a profound impact on fire behaviour; without fuel, a fire cannot propagate (Rothermel 1983; Price et al. 2014). Fire propagation and extinguishment are then a result of the expression of vegetation on the landscape. Fuel is a product of the bottom-up influence of topography and the resulting regional weather and the top-down influences of climate (Heyerdahl et al. 2001). Vegetation at a given location is a relatively stable component of the fire environment, changing slowly over time as the vegetation community develops, but can change dramatically and rapidly following disturbance events (Krawchuk and Moritz 2011). In the Canadian Rocky Mountains, vegetation age and species composition can vary widely across multiple spatial scales in response to localized weather, topography, and disturbance events of different sizes and intensities (Rogeau et al. 2016). The expression of vegetation over time and space results from the combination of topographic, weather, climate conditions, and past disturbance, which, in turn, affects fire spread and cessation.

Fire behaviour is influenced by fuel properties that are intrinsic, such as moisture content and chemical attributes (Richards 1940), and extrinsic, such as distribution and orientation in space (Pyne et al. 1984). The moisture content of vegetation varies temporally over hours, seasons, and years in response to environmental factors and decomposition of dead vegetation and woody debris (Van Wagner 1987). Concave valleys produce fuels with higher moisture content due to the pooling of cold air and moisture, producing wetland, riparian, and other poorly-drained vegetation communities that are not predisposed to burn (Andison 2012; Araya et al. 2016). In the Canadian Rocky Mountains, fire boundaries formed at avalanche paths connected to riparian areas (Suffling 1993).

Fire intensity is proportional to the quantity of fuel, that is, the weight or amount of vegetation available to burn (Van Wagner 1983). Fuel size and shape influence the amount of heat required to remove moisture and bring fuel to ignition temperatures, such that fuels with a larger surface-area-to-volume ratio enhance fire spread rates (Anderson 1970). The compactness of fuel particles influences moisture exchange, oxygen supply, and radiant energy transfer such that less compact fuels often have faster fire spread rates than denser fuels (Rothermel 1972). Due to the density of ground fuels, a compact matrix of roots, decaying wood, and decomposing vegetation, fire behaviour is limited to smouldering in the deep organic layers (Pyne et al. 1984).

The continuity of fuels influences a fire's ability to grow and propagate, such that when fuels are horizontally continuous, it is easier for fires to spread (Van Wagner 1977). Increasing crown closure is associated with increased potential for crown fires, which are difficult to stop unless another aspect of the fire environment reduces fire behaviour and spread (Schaaf et al. 2007). Likewise, the vertical continuity of fuels allows the fire to move from the ground, to surface, to ladder fuels, and finally to the canopy (Anderson 1982). Discontinuous fuels limit rates of spread, diminishing fire intensity and severity (Graham et al. 2004). Ferster et al. (2016) observed that in mountainous areas of Alberta, horizontally discontinuous fuels, a result of increased elevation and diminishing growing conditions, reduced vegetation mortality. In alpine environments of the western United States, discontinuous fuel patches developed in response to colder temperatures and decreased residual moisture (Holsinger et al. 2016). In horizontally patchy vegetation, fire spreads slowly by spotting instead of a continuous flame front such that fire boundaries correspond with sparsely vegetated ridges (Narayanaraj and Wimberly 2011). Fire behaviour responds to the physical components and properties of vegetation, how vegetation grows, decays, and burns.

To predict fire behaviour in common forest types, Canadian federal government researchers developed a fuel classification scheme and estimated models of fire behaviour for each fuel type as part of the FBP System (Forestry Canada Fire Danger Group 1992). The FBP System fuel types and equations for fire spread rates have formed the basis of many fire growth simulation models (Alexander et al. 2004). The FBP System defines 16 standard fuel types developed from experimental and prescribed fires, primarily in the Canadian boreal forest. As a result, these models are not well-suited to the fuel complex of the Canadian Rocky Mountains and consequently, predicted rates of spread represent best estimates of expected fire behaviour. In British Columbia, Biogeoclimatic Ecosystem Classification (BEC) zones identify vegetation assemblages and climate patterns (Meidinger and Pojar 1991), that can produce differences in fire behaviour across a given FBP System fuel type (Nitschke and Innes 2007).

In California, when fire disturbance occurs, it introduces negative feedbacks by consuming fuel, thereby limiting the likelihood and extent of future fires (Collins et al. 2009). Likewise in Australia and western North America, this effect may be strong immediately following a fire, but diminishes with time as the vegetation regrows (Price et al. 2014; Parks et al. 2015). The rates at which different ecosystems accumulate fuel reflect variations in regional expressions of climate and weather (Johnson et al. 1998). In the Canadian boreal forest, simulation modelling indicated previous burns have a protective effect for ten years following a fire, during which the probability of an ignition starting in a burned stand reduces (Erni et al. 2018). Empirical evidence suggests fires in black spruce can have a protective effect for up to 45 years under all but extreme weather conditions (Beverly 2017). Old burns also limit the potential for fire spread, resulting in historical fire boundaries abutting one another and creating the appearance of interlocking puzzle pieces across the landscape that represent various stages of post-fire regrowth (Amiro et al. 2001). In the northern Rocky Mountains of the United States, empirical data indicate that the ability of a stand to resist fire may persist for 20 years while in the dry southwestern United States, the effects persist for only 5-10 years (Holsinger et al. 2016; Parks et al. 2016). In Australia, empirical data indicates previous burns only effectively stopped fire spread for one year (Price et al. 2014). The self-limiting properties of fire can provide insight into the relationship between fuel and climate, with cold and moist environments characterized by extended periods of ecosystem memory in comparison with hot and dry environments.

The notion that site conditions influence the persistence of self-limiting fire properties is evident in observing re-generating stands. Parks et al. (2016) reported that higher moisture content of new fuels was the primary deterrent for fire spread in the western United States. In British Columbia, Spies and Franklin (1989) found that the density of vegetation regrowth increased fuel moisture contents and, in combination with decreased in-stand winds, inhibited fire spread. The moisture content of suckering aspens (*Populous tremuloides*) in the boreal also limits fire spread (Krawchuk et al. 2006). Similar situations presented across the western United States, where fires ignited in previous burns were naturally limited to less than 20 hectares (Parks et al. 2016). The self-limiting effect of fire is inconsistent; in ecosystems adapted to short fire return intervals, such as a Bunchgrass (*Festuca*) or Ponderosa Pine (*Pinus ponderosa*), vegetation regrowth quickly generates conditions conducive to fire spread (Harris and Taylor 2017). Burning may also introduce snags and downed wood, producing a fuel type similar to slash, which is susceptible to burning at high intensities even under average weather conditions (D. Schroeder, personal communication, March 8, 2017). The self-limiting properties of fire are not solely influenced by the occurrence of a burn, but rather the vegetation that regrows in response to bottom-up and top-down conditions of the environment.

Similar to the influence of weather and topography, fuel exerts a complex influence on fire cessation. The spatial and temporal variation of a fuel complex interact and are dependent on climate, weather, and topography. In the Canadian Rocky Mountains, further research is required to characterize the influence of vegetation on fire cessation at multiple scales.

1.3.4 Anthropogenic

Humans have influenced the fire environment for thousands of years by applying fire to the landscape intentionally and unintentionally (Syphard and Keeley 2015). The success of suppression efforts over the last century altered human influences (Pyne 2007). Fire managers intuitively incorporate natural fire environment features in fire suppression strategies and tactics. In Ontario, Podur and Martell (2007) reported that 25% of fire suppression lines were constructed along natural fire-cessation features, which were reinforced by hose lay and helicopter water bucketing. Likewise, in the Cascade Mountains of the United States, fire boundaries were associated with valley bottoms and related road networks (Narayanaraj and Wimberly 2011). Fuel management treatments aim to mitigate fire risk by reducing available fuels through mechanical thinning, delimbing, and prescribed burning (Agee and Skinner 2005). However, contradictory evidence from the Cascade Mountains of Idaho suggests that treated areas can burn at higher intensities and/or severities than the surrounding forest (Hudak et al. 2011). Fire managers must be confident that a fuel treatment, which is effectively a pre-positioned fireguard, will succeed in slowing fire spread and reducing fire intensity, should a fire encroach on the location. Further research is necessary to determine the effects of anthropogenic influences on the fire environment and subsequent fire cessation.

1.3.5 Fire Environment Synthesis

All aspects of the fire environment must be conducive to spread, or fire growth will cease (Rothermel 1983). Andison (2012) and Ferster et al. (2016) caution that the processes of fire refugia formation and fire cessation differ in their relationship to the fire environment. The relative importance of fire environment variables on fire cessation is expressed differently across ecosystems, resulting in a highly complex research challenge, in contrast to the traditional view that fire is either limited by fuel or weather (McKenzie and Kennedy 2012). The complex interactions further support Bradstock's (2010) switch model of fire propagation that there must be (1) fuel that is (2) available to burn in (3) weather conducive to spread (4) with adequate ignition sources. By understanding how fire environment factors including suppression efforts result in fire cessation, fire modellers will be better able to predict fire cessation as a component of fire growth.

1.4 Sample Distances in Previous Studies

Recent research on fire boundary formation has focused on comparing environmental differences inside the fire perimeter to those outside the fire; however, studies of fire perimeters are challenged by factors that confound the identification of suitable sample points. Fire boundaries are presented and mapped as sharp discontinuities between burned and unburned states. Ecological boundaries are inherently challenging to delineate due to the uncertainty and subjectivity of the mapping process (Gosz 1991; Andison 2012). Fire boundaries may indeed form rapidly and present as discrete locations, but they may also develop slowly, resulting in ecotones, transitional areas of diminishing fire intensity and severity over hundreds of metres (Forman 1995). In south-central British Columbia, transition zones associated with fire boundaries had widths ranging from 0 m to 127 m (McIntire and Fortin 2006). Operational perimeters are often mapped at a relatively coarse resolution, while satellite mapping lacks the spatial precision to accurately map detailed fire boundaries and detect low severity burned areas (Kolden et al. 2012). The limited spatial precision and accuracy of fire polygon records introduce significant challenges for studying the process of fire perimeter formation.

The objective of a fire boundary study is to understand how the fire environment influences fire cessation; however, a consensus has not been reached as to the best sample distance to capture fire boundary formation. Some studies have attempted to understand fire boundary formation at broad distances by comparing interior sample locations to those of the fire boundary. Andison (2012) assessed the differences between burned, refugia, and remnant areas – bays of unburned vegetation contained within a smoothed version of the fire perimeter using buffers at 50 m increments up to 500 m. Povak et al. (2018) examined the differences between a 100 m interior buffer of the fire edge to the total interior area of the fire. Holsinger et al. (2016), sampled points every 3000 m along the fire perimeter and paired points within the fire's core, representing 50% of the area burned. Price et al. (2014), used a circular neighbourhood with a 500 m radius located at 2000 m intervals along the fire perimeter and compared them to paired observations located 1000 m inside the fire perimeter. Other studies have investigated the process of fire boundary formation at finer distances. Narayanaraj and Wimberly (2011) sampled every 200 m along the fire perimeter and paired these locations with matched points at 100 m intervals up to 500 m along a perpendicular transect inside the fire. O'Connor et al. (2017) compared 30 m pixels along the fire boundary to pixels directly adjacent to the interior of the fire boundary.

Comparisons among studies are complicated by the varying sample distances used to capture different landscape patterns and processes (Turner et al. 1989). With increasing distance from the area of interest, fine-scale processes may be obscured, causing broader processes to dominate observations. It is difficult to assess and compare the results of each study without understanding the influence of the sample distance on model outcomes.

1.5 Research Opportunities

The relationship between fire environment and fire cessation is a developing area of fire science. Current research indicates the relative importance of weather, topography, fuel, and anthropogenic influences varying across ecoregions. To date, empirical studies of the relationship between fire cessation and the fire environment are limited to Australia, the western United States, and Alberta. As of yet, no research has addressed fire cessation in the western Rocky Mountains of Canada despite the risk to many communities from fire. Among the studies of fire cessation, each has employed a different sample distance and statistical method, and few have validated their model's predictive ability across broader landscapes. To date, no investigations have specifically addressed how the sample distance influences conclusions about fire environment processes on fire cessation.

1.6 Research Objectives

This thesis investigates interactions between fire environment conditions and fire cessation. The specific objectives are: (1) characterize how the fire environment (weather, topography, fuel, and anthropogenic variables) influences fire cessation; (2) evaluate the impact of analysis distance on the predictive ability of fire environment variables for estimating the probability of fire boundary formation; (3) interpret results of fire cessation model outputs for ease of use in management applications.

To meet these objectives, I selected a case study fire, the 2017 Verdant Creek Fire, and completed a comprehensive review (Smith 2018) to document fire weather, behaviour, and management operations during the fire. I then developed a series of statistical models using varying sample distances and temporal scales to assess the relationship between fire boundary formation and a suite of fire environment factors generated for my case study fire. I compared statistical models based on their predictive ability to detect fire boundary locations and selected a sample distance best suited to capture the fire cessation process. I then performed a series of re-analysis to identify the influence of fire management on fire boundary formation. I developed a Spread Potential Index (SPI) to visualize and interpret spatial variation in the potential for fire boundary formation across a landscape. In doing so, I aimed to understand how the fire environment influences fire cessation in the western Rocky Mountains of Canada adjacent natural regions of western Canada while also contributing new insight about how sample distances influence our understanding of the relationship between the fire environment and fire cessation.

Chapter 2 Methods

2.1 Study Area and Fire Event

The study area encompasses 179 650 ha within two adjacent protected areas in the Canadian Rocky Mountains (Figure 1): Kootenay National Park (KNP) and Mount Assiniboine Provincial Park (MAPP). Although the prevailing climate is continental with long cold winters and brief cool summers, orthographic uplift and the resulting precipitation produce a slightly more maritime variant (Environment Canada 1984). Young seral stands, often in valleys, are a mix of lodgepole pine (*Pinus contorta*) and grasses. Engelmann spruce (*Picea engelmannii*), white spruce (*Picea glauca*), and subalpine fir (*Abies lasiocarpa*) dominate mature forests.

Though KNP and MAPP have a history of fire management favouring suppression (Masters 1989), fire remains the dominant natural disturbance on the landscape as a mixed-severity fire regime (Kubian 2013). Between 1914 and 2017, 223 fires burned 45% of the total area of KNP, and between 1936 and 2017, fires burned 25% of the total area of MAPP, or an average annual percent burned of 0.43% and 0.30%, respectively. From 1991 to 2018, the Vermillion Valley experienced six fires of significant extent (300 – 18000 ha, mean 7000 ha). Human and lightning-caused ignitions occur predominantly in late July and August, however; lightning fires are attributed to major fires as many fires often ignite at once overwhelming firefighting resources. Small, low-intensity fires are suppressed and generally only escape initial firefighting efforts under extreme weather conditions (Weir et al. 1995). When fire conflagrations occur, they are high-intensity stand-initiating crown fire events with patches of moderate severity surface and ground fire which maintain the stand structure (Cochrane 2007; Kubian 2013). The return time for fires in the forests of KNP and MAPP is 60 to 350 years (267 years in the Vermillion Valley), forest types near the valley bottom burned more frequently than those in the alpine (Masters 1990; Wong et al. 2003). The fire regime may be shifting as recent fires have increased area burned since Masters (1990), indicating a potential shift towards more frequent stand replacing fires, shifting vegetation assemblies and stand structure (Hallett and Walker 2000; Hallett and Hills 2006).

Ignition of the Verdant Creek Fire occurred by lightning strike in early July 2017 and by September 2017 had achieved a final size of 18 000 ha. Fire suppression efforts by Parks Canada and the British Columbia Fire Service were limited to critical areas of the fire to protect values at risk, which means the process of fire spread and fire cessation were predominantly uninhibited by human intervention, thus providing ideal conditions for studying natural fire environment influences on the formation of fire boundaries.

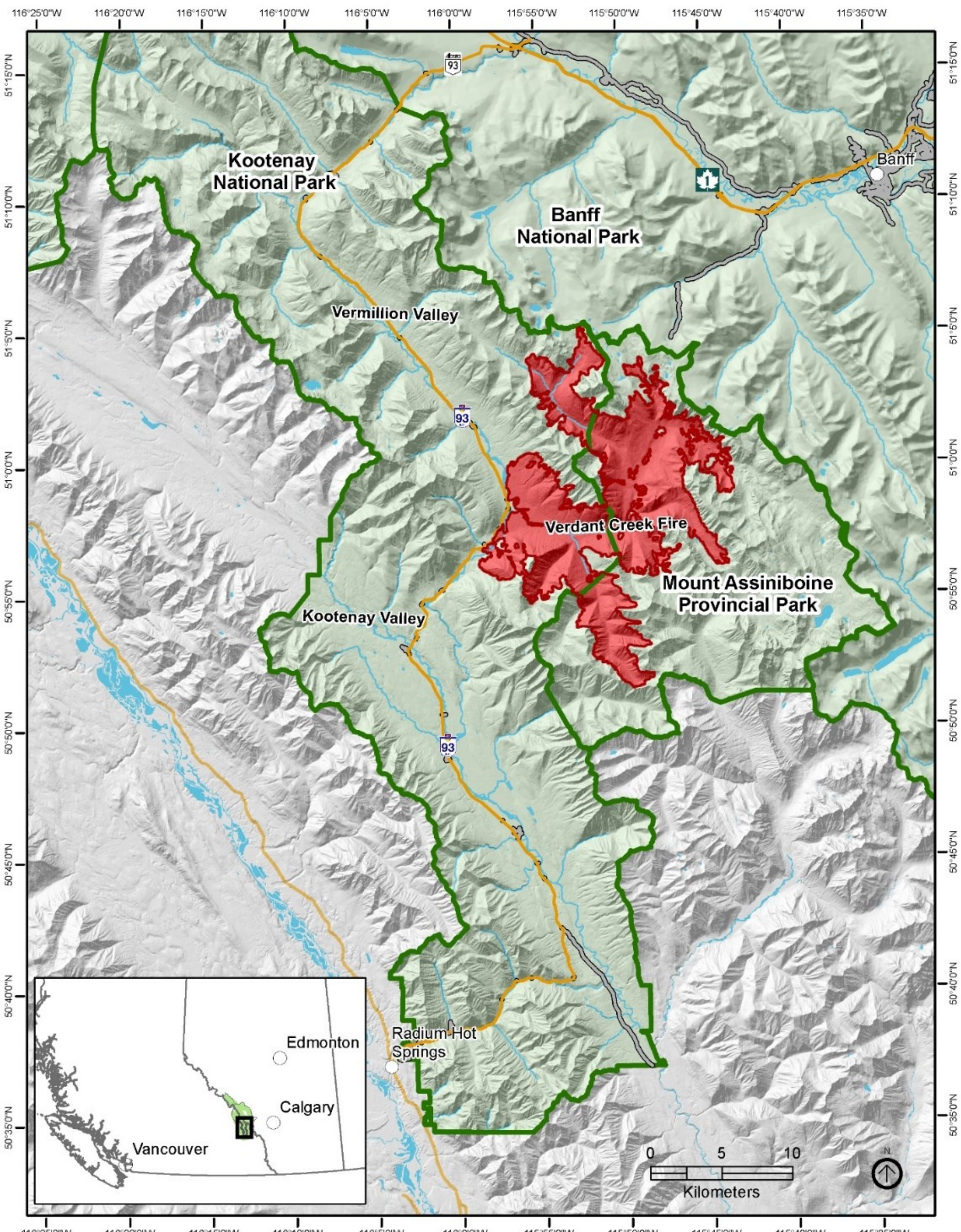

Figure 1: Location of the study area, the 2017 Verdant Creek Fire, in the Canadian Rocky Mountains. Orography defines the western Continental Range Ecozone; north-south trending valleys are steep and narrow, ranging from 1300 m to 2100 m.

2.2 Fire Perimeter Mapping and Sampling Design

I retrieved an agency-derived fire polygon of the Verdant Creek Fire from Parks Canada, which was captured using a helicopter and a handheld global positioning receiver (GPS). Fire perimeters obtained in this manner are recognized as having positional location, and manual mapping errors, which result in overestimates of area burned (Li et al. 2005; Kolden and Weisberg 2007). I verified the perimeters accuracy by comparing it with post-fire imagery from Landsat-8 (United States Geological Survey 2019), and Sentinel (European Space Agency 2019) acquired the year following the fire. Results indicated that the operational perimeter did not adequately represent the actual area burned. To correct the perimeter, I retrieved a second fire delineation of the fire edge derived from the National Burned Area Composite (NBAC) (Canadian Forest Service 2017). The NBAC final fire perimeter is complete with fire refugia (unburned areas within a fire perimeter), and burned islands (burned areas outside the fire perimeter). The NBAC uses the difference Normalized Burn Ratio (dNBR) method, which compares Landsat imagery before and after a fire to detect and map burn severity or the magnitude of vegetation change following a fire (Soverel et al. 2010). Fire perimeters derived from the dNBR method are better suited to capture actual fire perimeters (Kolden and Weisberg 2007).

To document fire progression and date of burning, I employed a methodology developed by Parks (2014). I retrieved fire detection data from Moderate Resolution Imaging Spectroradiometer (MODIS) (Schroeder et al. 2008) and Visible Infrared Imaging Radiometer Suite (VIIRS) (Schroeder et al. 2014). R-code provided by Parks (2019, personal communication, Dec 6, 2019) was used in combination with verified fire progression dates compiled from operational data. The code rasterized the fire area into 30 m pixels and assigned each pixel a "day of burning" using a weighted average to the nearest VIIRS or MODIS hotspots. I created points spaced every 30 m along the fire perimeter and assigned a date of burning using the nearest pixel. I used these points to visualize daily fire growth, and fire perimeter formation by comparing the daily proportion of points that burned to the total number of points (Price et al. 2014).

Following a sampling resolution determined by Narayanaraj and Wimberly (2011) to adequately capture variability in fire boundary attributes, I systematically sampled sites every 200 m along the fire perimeter in ArcGIS. At each location, I established linear transects subdivided by and perpendicular to the fire perimeter and selected sample points along both the burned and unburned segments of the transect at the following distances from the fire perimeter: 40 m, 100 m, 200 m, 300 m, 400 m, and 500 m (Figure 2). I manually inspected each point in ArcGIS, removing any points with incorrect placement inside or outside the perimeter, or in refugia and burned islands. This methodology ensured that no sample point, classified as a burned location, occurred in an unburned or fire refugia areas, and no unburned points occurred in burned islands outside the fire perimeter.

Selection of explanatory variables occurred in two stages. Following an initial literature review of fire spread, refugia, and boundary formation, and discussions with local fire managers, I drafted a preliminary list of potential explanatory variables. From this initial set, I defined seven weather variables (Table 1), and twelve topographic, fuel, and anthropogenic variables (Table 2). All variables met the following criteria: they were readily available to fire management agencies in British Columbia, simple to derive, and contained limited null values in the study area.

For each sample point, I extracted a suite of explanatory variables describing the date of burning, anthropogenic, topographic, and vegetation conditions at that specific location. To determine the influence of weather, I used the date of burning for each sample point and associated weather variables from the Vermillion Weather Station; the nearest weather station located 3 – 21 km from the fire perimeter (average 12 km). To explore the influence of temporal weather changes on extinguishment, I followed the approach used by Holsinger et al. (2016). Using the associated date of burning, I assigned interior sample points associated with daily weather variables. For the perimeter points, I assigned weather variables 1- and 3-days following the reported day of burning. I was able to incorporate the potential effects of diminishing fire weather on fire cessation by delaying perimeter weather variables (Latham and Rothermel 1993; Holsinger et al. 2016).

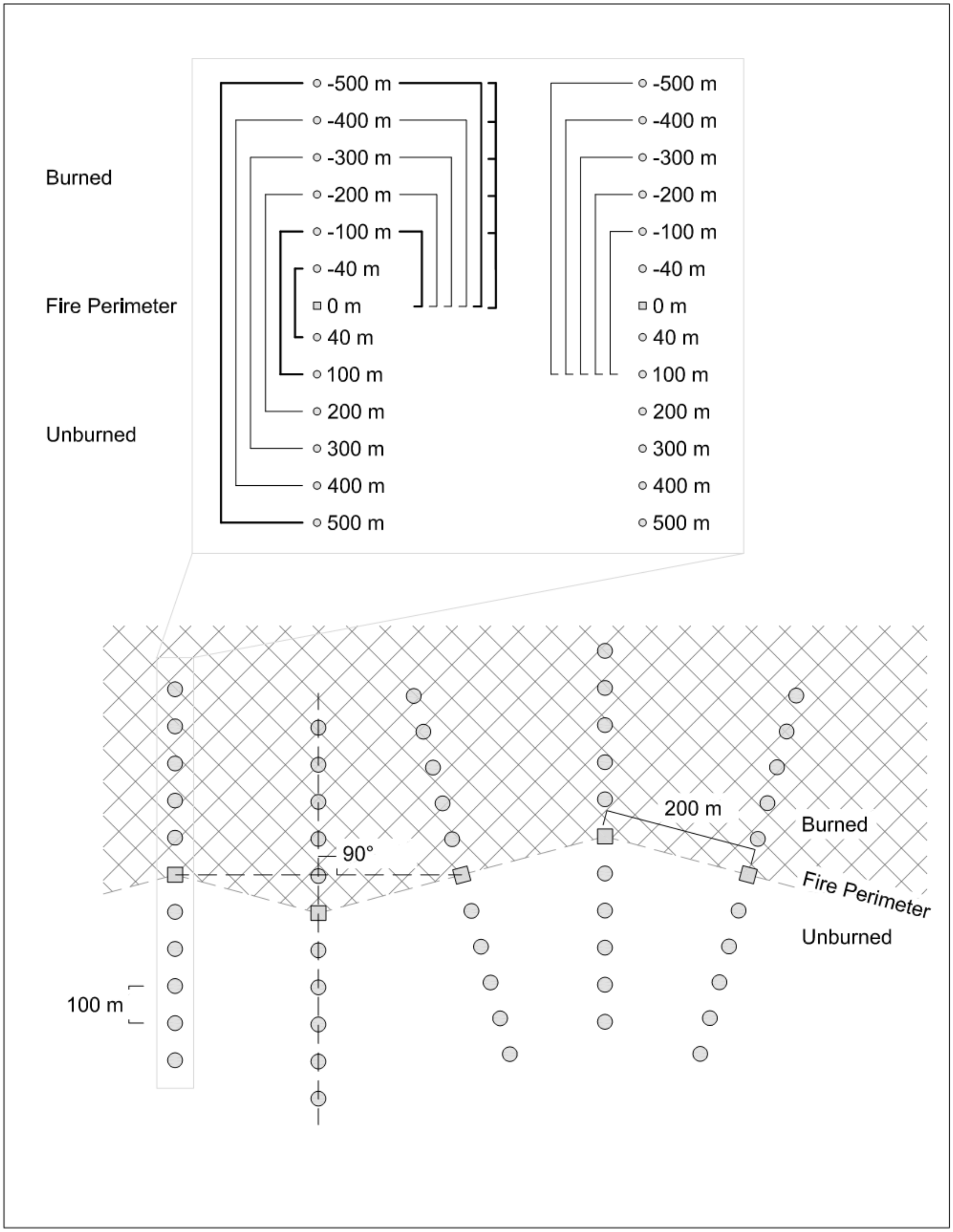

Figure 2: Sampling methodology for the stable fire environment and unstable weather models. Initial sample points were located every 200 m along the fire perimeter with perpendicular points established inside and outside the fire perimeter. In total, 16 distances of analysis were developed (after accounting for one duplication), equidistant paired models (6 models), 0 m exterior paired to different interior distances (6 models), 100 m exterior paired to different interior distances (5 models). In the top panel, light grey lines indicate all sample groupings available in results; bold lines indicate pairs presented in results. The weather models used only the 0 m compared to -100 m and -500 m.

Table 1: Explanatory weather variables used to fit fire boundary models

Variable	Units	Description	Source
Weather			
Wind	km/h	The maximum daily speed of air parcel movement.	Parks Canada – Vermillion Weather Station
24-hour rain	mm	Amount of precipitation received between 1200 LST current day and the previous 24 hours	Parks Canada – Vermillion Weather Station
72-hour rain	mm	Amount of precipitation received between 1200 LST current day and the previous 72 hours	Parks Canada – Vermillion Weather Station
Vapour Pressure Deficit (VPD)		The maximum daily Vapour Pressure Deficit (VPD), the difference between the saturation vapour pressure of the air, and the actual vapour pressure of the air mass. Derived from hourly temperature and relative humidity	Parks Canada – Vermillion Weather Station Lawrence, 2005
Fine Fuel Moisture Code (FFMC)	unitless	The Fine Fuel Moisture Code (FFMC) tracks daily changes in litter fuels due to variations in weather – temperature, relative humidity, precipitation, and wind speed observed at 1200 LST.	Parks Canada – Vermillion Weather Station Van Wagner 1987
Initial Spread Index (ISI)	unitless	The Initial Spread Index (ISI) incorporates the effects of changes in Fine Fuel Moisture Codes (FFMC) and wind speed observed at 1200 LST on fire spread rate. Higher values indicate increased spread rates.	Parks Canada – Vermillion Weather Station Van Wagner 1987
Fire Weather Index (FWI)	unitless	The Fire Weather Index (FWI) incorporates the effects of daily changes Initial Spread Index (ISI) and Build-up Index (BUI) on expected fire intensity per unit length of fire line. Higher values indicate increased intensity.	Parks Canada – Vermillion Weather Station Van Wagner 1987

Table 2: Explanatory topographic, fuel, and anthropogenic variables used to fit fire boundary models

Variable	Units	Description	Source and Processing
Topographic			
Distance to waterways	Kilometers	Distance to nearest river or stream	Parks Canada Hydrology - ArcGIS
Slope	Percent	The difference in elevation over horizontal distance expressed as a percentage	Parks Canada DEM - ArcGIS
Heat Load Index (HLI)	Unitless	Uses aspect, slope, and latitude to determine potential direct incident radiation, slope temperature. Values range from 0-1. Increasing values indicate warming	Parks Canada DEM – ArcGIS Reference: (McCune and Keon 2002; Evans et al. 2014)
Topographic Wetness Index (TWI)	Unitless	Uses catchment areas and surrounding slope gradient to determine potential areas of soil water pooling using a 3 m by 3 m moving window. Higher values indicate an increase in potential soil wetness	Parks Canada DEM - SAGA GIS Reference: Böhner and Selige, 2006
Topographic Convergence Index (TCI)	Unitless	Uses catchment areas and surrounding slope gradient to determine potential areas of cold air pooling using a 3 m by 3m moving window. Higher values indicate an increase in potential cold air pooling	Parks Canada DEM - SAGA GIS Reference: Conrad et al. 2015(Conrad et al. 2015)
Topographic Position Index (TPI)	Unitless	Compares elevation of each cell to detect ridges (positive) and valleys (negative), transformed to absolute values as other studies have noticed that fire perimeters' were associated with both. Higher values indicate ridge or valleys	Parks Canada DEM - SAGA GIS Reference: Conrad et al. 2015
Fuel			
Fire Behaviour Prediction (FBP) Grid	Discrete	Vegetation classified according to the Canadian Forest Fire Behavior Prediction (FBP) System fuel types, includes water bodies and non-fuel	B.C. Fire Service
Biogeoclimatic (BEC) Zones	Discrete	MS (Montane Spruce), dk – dry cool ESSF (Engelmann Spruce subalpine fir), dk – Columbia dry cool, dku – transition area between dk or dkw and dkp , dkp – dry cool parkland. dkw – dry cool woodland IMA (Interior Mountain Heather Alpine), un – undifferentiated	B.C. VRI BEC_zone and BEC_variant
Wetland	Discrete	Areas where the water table is near or above soil sources Such as wetlands, bogs, fens, marshes, swamps, shallow water	B.C. VRI BCLCS_Level_3
Shrubs	Discrete	Shrub Low, shrubs in a polygon are under 2m Shrub tall, shrubs in a polygon are over 2m	B.C. VRI BCLCS_Level_4
Herbaceous	Discrete	Non-defined herbaceous and graminoid cover. Describe regrowth following the 2001 and 2003 Vermillion Valley fires	B.C. VRI BCLCS_Level_4
Density	Discrete	Describes horizontal distribution of trees, shrubs, or herbs (Dense – 61-100 %, Open – 26-60%, Sparse – 10-25%	B.C. BC VRI BCLCS_Level_5
Crown Closure	Continuous class (1-10)	Percentage of polygon covered by all layers of tree crowns	B.C. VRI crown_closure_class_cd
Stand Age	Age	Projected standage of leading species	B.C. VRI proj_age_1
Anthropogenic			
Distance to roads	Meters	Distance to the nearest paved or unpaved road	Parks Canada transportation data

2.2.1 Weather

I defined seven weather variables for analysis to detect the influence of weather on fire cessation (Table 1). Similar to Podur and Wotton (2011), Ferster et al. (2016), and Holsinger et al. (2016), I included variables from the FWI System: FFMC, ISI and FWI values detect if the fire was influenced by these respective indicators of ignition receptivity, fire spread rate, and intensity. I excluded DMC, DC, and BUI as predictor variables due to their lengthy reaction times to abrupt and potentially fire-ending weather events. Fire cessation is often attributed to precipitation (Latham and Rothermel 1993). To account for the cumulative effects of precipitation, I defined two precipitation variables: total rainfall during 24- and 72-hour periods from the date the fire boundary formed. VPD was used to provide a measure of the evapotranspiration potential of the environment that combines temperature and relative humidity (Lawrence 2005). Higher VPD values are associated with fire growth (Sedano and Randerson 2014; Seager et al. 2015) and lower values with fire cessation (Just et al. 2016). Likewise, wind speed is a recognized driver of fire spread (Rothermel 1972). To account for daily fluctuations in wind speed and VPD, I used maximum daily values.

2.2.2 Topography

To quantify the influence of topography on fire cessation, I selected variables shown to influence fire behaviour or fire cessation in previous studies: slope, HLI (Povak et al. 2018), TWI, TCI, (Krawchuk et al. 2016), and TPI (Holsinger et al. 2016) (Table 2). I used distance to the nearest waterway due to the use of waterways for control lines in the Canadian Rocky Mountains, similar to the "distance-to-roads" metric used by Narayanaraj and Wimberly (2011) to capture linear features relevant to fire suppression operations. To capture the influence of hydrology, I used a 30 m digital elevation model (DEM) and waterways layer that encompassed both KNP and MAPP (M. Beaujot Parks Canada, personal communication, August 28, 2018). In ArcGIS, I calculated the slope percentage for each 30 m cell and created 30 m rasters of distance to the nearest waterway (ESRI 2019). I also created a 30 m HLI raster using the Geomorphometry and Gradient Metrics Toolbox (Evans et al. 2014). HLI integrates latitude, aspect, and slope into a unitless index of incident radiation (McCune and Keon 2002). In SAGA GIS (Conrad et al. 2015), I computed 30 m rasters of TWI and TCI using a 3 x 3 cell moving window and TPI using a 500 m radius circular window. TWI and TCI use catchment areas and the surrounding slope gradient to produce unitless indexes. TWI increases with potential soil wetness and TCI increases with potential for cold air pooling. TPI is used to describe the difference between the elevation of a central cell and the mean of its surrounding cells to determine valleys (negative) and ridges (positive); however, given that both valleys and ridges are associated with fire boundaries, I converted the initial values to an absolute value (Holsinger et al. 2016).

2.2.3 Fuel

I defined seven variables that characterized different aspects of the fuel complex within the study area (Table 2). The FBP System fuel type classification is used to estimate fire rates of spread (Alexander et al. 2004) and thus is expected to also indicate variation in fire cessation processes. The 2016 provincial FBP System fuel type grid was obtained from the British Columbia Fire Service and included fuel type classifications for vegetated areas as well as non-fuel and water classifications at a 50 m x 50 m cell size (D. Hay, personal communication, Feb 5, 2019). For the remaining fuel attributes, I used vegetation and land classifications from the 2016 Vegetation Resource Inventory (VRI) dataset (BC Forest Analysis and Inventory 2019), which I converted to a 30 m x 30 m raster. BEC data contained in the VRI dataset groups areas of similar vegetation and topography into zones with further subdivisions based on temperature, precipitation, and phases such as parkland or woodland sites (MacKenzie and Meidinger 2017). Differences in BEC zones have been shown to modify fire behaviour in FBP System fuel types (Nitschke and Innes 2007) and may influence fire cessation.

Vegetation assemblages associated with avalanche and riparian areas were shown to stop fire spread in the eastern Canadian Rockies (Suffling 1993), while wetlands have diminished fire spread in the eastern United States (Hirsch and Fuglem 2006). I used existing VRI classifications of shrubs for avalanche paths and vegetation associated with rivers and streams and wetland-classified data to capture the influence of plant assemblages related to wetland, riparian, and aquatic processes. As fuel continuity and horizontal distribution influence fire spread (Schaaf et al. 2007) and fire cessation (Narayanaraj and Wimberly 2011), I used VRI classifications of stand density and crown closure as potential explanatory variables. To capture the influence of previous burns and changes in the fuel complex that coincide with stand developmental stage (Price et al. 2014; Holsinger et al. 2016), I used VRI classifications of stand-age and the herbaceous cover which described regrowth following the 2001 and 2003 fires in the Vermillion Valley.

2.2.4 Anthropogenic

I selected two potential variables to represent the influence that humans have on fire spread. Following prior studies that found road networks influence fire cessation (Narayanaraj and Wimberly 2011; O'Connor et al. 2017), I used paved and unpaved road data (M. Beaujot Parks Canada, personal communication, August 28, 2018), to derive a 30 m x 30 m raster of the distance to the nearest roadway in ArcGIS (Table 2). I explored the viability of including data on control line locations (O'Connor et al. 2017) in my statistical models; however, reliable and complete records of operational activities along the fire perimeter were unavailable. In managing the Verdant Creek Fire, Parks Canada, and the British Columbia Fire Service focused on critical areas of the fire to protect values at risk such that fire cessation was predominantly uninhibited by human intervention (Smith 2018). Suppression activities are spatially and temporally dynamic features of the fire environment. The potential impact of suppression on fire cessation is explored through a re-analysis in 2.3 Statistical Modelling.

2.3 Statistical Modelling

I divided statistical modelling into two sections depending on the temporal longevity of variables and potential applications in fire management (Figure 3). Fuels, topography, and anthropogenic influences included are relatively static over temporal scales of analysis, as long as no disturbance occurs. As a result, the stable aspects of the fire environment are useful for strategic landscape planning (1–5 years). In contrast, weather fluctuates widely over temporal and spatial scales and is better suited to operational decisions in the immediate future (1–14 days). By separating dynamic factors of the fire environment from relatively fixed factors, it is possible to produce applications with potential for strategic planning and reactive fire management.

To explore the impact of the fire environment, weather, fuels, topography, and anthropogenic factors on fire boundary formation, I used matched case-control conditional logistic regression (MCC Clogit). This method was initially used in biomedical research to detect the odds of a disease occurring given preceding conditions (Breslow and Day 1980). Like other fire boundary studies (Narayanaraj and Wimberly 2011; Holsinger et al. 2016), I applied the MCC approach to detect the odds that a fire boundary will form at a given location using stable fire environment variables. I compared fire environment variables at unburned (case) and burned (control) locations. As in standard in conditional logistic regression, I coded cases (perimeter and unburned locations) as

“1”, and controls (burned locations) as “0” for each sampling transect. Spatial autocorrelation is considered an inherent component of most ecological data, caused by top-down and bottom-up influences at both small and broad scales, potentially causing confounding effects when sampling locations are spatially structured (Fortin 1999; Narayanaraj and Wimberly 2011). By pairing cases and controls by their location along the fire perimeter, potential issues of spatial autocorrelation are reduced (Narayanaraj and Wimberly 2011). Spatial autocorrelation is an inherent component of ecological data

Fire boundaries are belts of diminishing fire intensity but are mapped as linear discrete features (McIntire and Fortin 2006), as such analysis distance may influence interpretations of fire cessation. Sample points must be independent of the fire cessation ecotone to assess the differences between burned and unburned areas. To detect this potential influence, I completed and compared the importance of different distances of analysis for both the dynamic (weather) factors and the stable (fire, topography, and anthropogenic) factors of the fire environment.

To detect the influence of weather on fire perimeter formation, I compared sample points on the unburned fire perimeter (i.e., 0 m), to each sample point located on the burned segment of the transect at 100 m, and 500 m distances from the perimeter (Figure 2). For topography, fuel, and anthropogenic variables, which are relatively stable over strategic planning horizons, I selected groups of variables based on three sampling scales of analysis (Figure 2). I compared sample points on the unburned fire perimeter (0 m), to each of five sample points located on the burned segment of the transect at 100 m intervals to a maximum distance of 500 m from the perimeter. To explore whether or not sample locations at a distance outside the fire perimeter were more effective for modelling than points located directly on the fire perimeter, I defined five additional unburned sample points at 100 m intervals along the unburned segment of the transect to a maximum distance of 500 m from the fire perimeter. I estimated five models by pairing the fire perimeter sample at 0 m with a matched pair on the burned segment of the transect (i.e., -100 m, -200 m, …-500 m). I estimated an additional five models using matched pair comparisons between sample points at equidistant intervals on each segment of the transect (i.e., burned and unburned), for example, matching sample locations -300 m inside the fire perimeter to locations 300 m outside the fire perimeter. To explore possible finer-scale processes, I included one very proximate matched pair of sample points just 80 m apart, at distances of 40 m and -40 m from the perimeter. I selected this distance as it was the smallest possible sample distance, given the resolution of my landcover data. I completed no further analysis at 40 m intervals due to the nature of fire boundary formation (McIntire 2004; McIntire and Fortin 2006) and the resolution of the data. In total, I defined 16-datasets of sample point pairs and estimated a statistical model for each dataset.

I tested for multicollinearity among the explanatory variables using the Variance Inflation Factor (VIF). I removed any variables with a VIF value greater than three in sequential order from highest to lowest (Zuur et al. 2010). Once I had selected covariates, I built a MCC Clogit model based on sampling pairs using the Survival Package in R (Therneau and Lumley 2019). Purposeful selection of covariates followed strategies outlined in Hosmer et al. (2013). I assessed candidate covariates using statistical significance with the individual p-value and the Akaike's Information Criterion (AIC). I estimated model fit using the concordance statistic, the new standard output of the Clogit model, equivalent to the area under the Receiver Operating Characteristic (Therneau and Lumley 2019). Concordance values range from 0.5 – 1, with an acceptable model scoring a 0.7 and an excellent model scoring a 0.8 or above (Hosmer et al. 2013).

Statistical modelling occurred independently for each sample distance, with individual components of the fire environment assessed separately (Equation 2). Similar to Holsinger et al. (2016) to assess the influence of stochastic aspects of the fire environment on fire cessation, I developed two temporally separate weather models using the 1- and 3-day delayed perimeter weather variables (Equation 2a and 2b, respectively). To assess the static influences of the fire environment on fire cessation, I developed individual models to assess anthropogenic, topographic and fuel models (Equation 2c, 2d, and 2e, respectively). Significant variables from the individual static models were combined into a final predictive model to assess the influence of the stable fire environment on fire cessation (Equation 2f). For the stable fire environment model, I then assessed the influence of clinically significant first-order interactions and retained any that were significant at the 1% level.

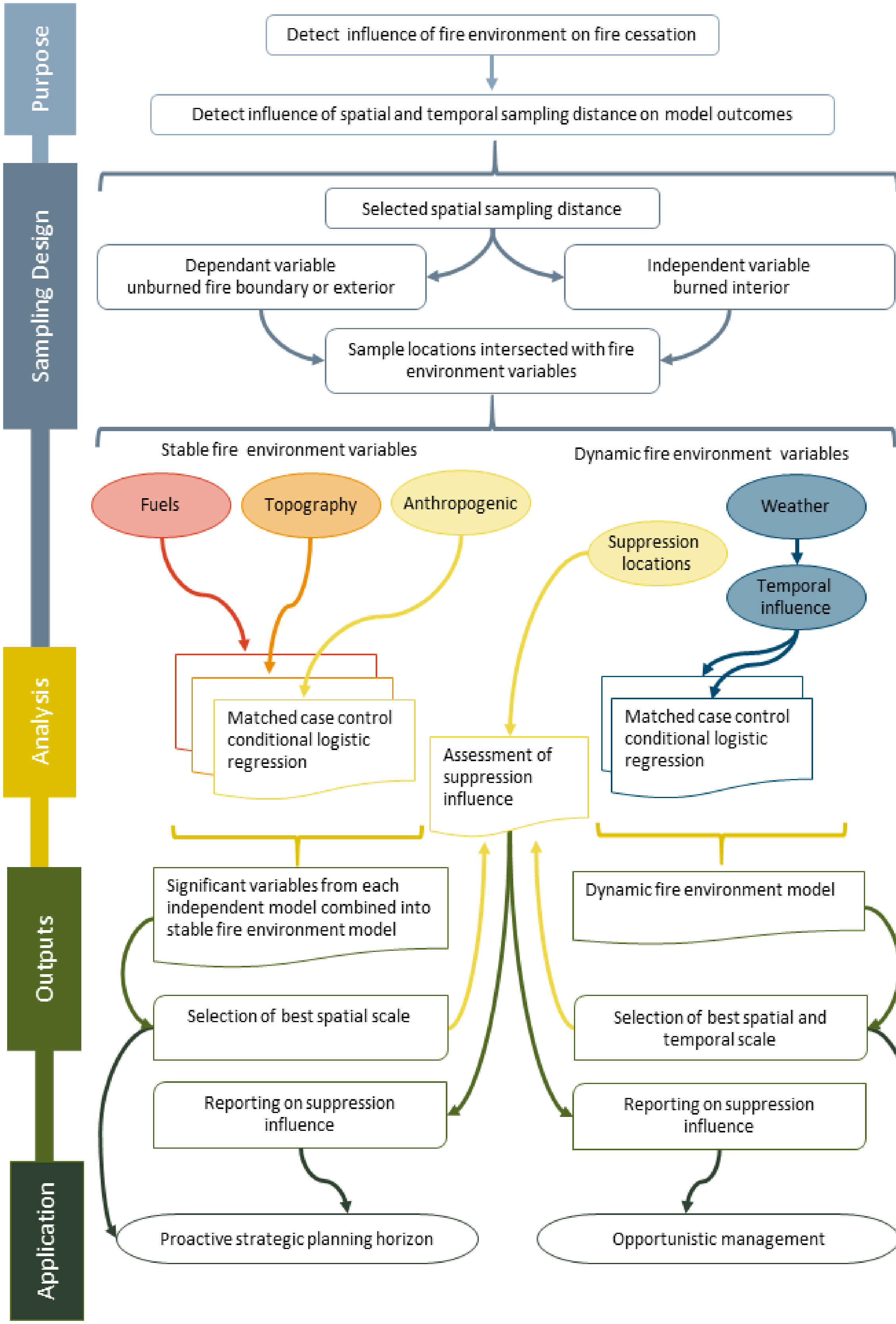

Figure 3: Flowchart of study design and data analysis process

Equation 2: Dynamic aspects of the fire environment are explored in the 1- and 3-day model (2a and 2b, respectively). The weather models (2a and 2b) were assessed at two sampling scales. Stable elements of the fire environment are explored in the anthropogenic(2c), topographic(2d), and fuel (2e) models. Significant variables from the stable fire environment are combined into the final stable fire environment model(2f). Aspects of the stable fire environment (2c-f) were assessed at 16 sampling scales.

a) 1-day weather model

Clogit (P-unburned) = Wind + Rain (24 hours) + VPD + FFMC + ISI + FWI+ strata pairs

b) 3-day weather model

Clogit (P-unburned) = Wind + Rain (24and72 hours) + VPD + FFMC + ISI + FWI + strata pairs

c) Anthropogenic model

Clogit (P-unburned) = Distance to nearest road +strata pairs

d) Topographic model

Clogit (P-unburned) = Distance to waterways + slope + HLI + TWI + TCI + TPI + strata pairs

e) Fuel model

Clogit (P-unburned) = FBP + BEC + wetland + shrubs + density + crown closure + stand age + strata pairs

f) Stable fire environment model

Clogit (P-unburned) = Anthropogenic + Topography + Fuel + interactions + strata pairs

2.4 Model Comparisons and Validation

For the weather model, I compared the predictive ability of each temporal and spatial scale. By comparing the four models, I identified the best sample distance and temporal scale to understand the influence of weather on fire cessation. For each stable fire environment model, I generated a surface probability map using the Raster Calculator function in ArcGIS. I used a probability threshold of 0.6 to define a predicted fire cessation point (i.e., estimated unburned location) and compared estimated status (i.e., burned versus unburned) with observed status. For example, inside the fire perimeter, a point with a probability under 0.6 is a correct classification. In contrast, in the unburned area outside the fire perimeter, a probability greater than 0.6 is a correct classification. I also compared each model's ability to classify exterior sample points as unburned (sensitivity), and classify interior sample points as burned (specificity) for all points sampled (Parikh et al. 2008; Figure 2). This model comparison assisted in identifying the best sample distance for detecting influences of the fire environment on boundary formation.

As factors included in the stable fire environment are relatively static over time, there is potential to use model results in strategic land management planning. I developed the Spread Potential Index (SPI), the inverse of the spatial probability map of being unburned, to detect if the model could be used to distinguish potential for fire cessation and fire growth. For example, an area with a low spread potential would have a higher probability of being a fire perimeter and would be expected to slow fire growth. In contrast, an area with a higher spread potential would have a reduced probability of being a fire perimeter and would be expected to exhibit enhanced fire growth.

A re-analysis of the best models detected the potential influence of suppression on fire perimeter formation. I identified and removed any sample points, which occurred in areas of known suppression (ground firefighting, retardant application, and aerial ignition). I then re-ran the statistical modelling process on the best weather (1- and 3-days) and stable fire environment models using the reduced data set to observe any differences in model outcomes. Finally, I compared the spatial predictive ability to detect burned and unburned areas for the best stable fire environment model.

Chapter 3 Results

3.1 Fire Weather and Growth

The Verdant Creek Fire was active for 56 days from July 14th to September 8th, 2017 and experienced three periods of growth and associated boundary formation (Figure 4). Throughout the fire, the maximum daily temperature averaged 28°C and the minimum relative humidity 20%, producing an average maximum VPD of 37 (Figure 5). Three major rain events during the duration of the fire totalled 26.5 mm, reducing FFMC and DMC, and subsequently, fire spread in the days that followed (Figure 6). High VPD meant that FWI index values recovered quickly following precipitation, supporting subsequent fire growth. When fire growth stopped in early September, there was no apparent fire-ending weather event. Instead, fire spread diminished progressively from September 1st – 8th, indicating gradually weakening fire weather. Strong morning inversions in early September trapped smoke in the valleys and reduced fire behaviour and, the arrival of a cold front on September 3rd brought spotty precipitation that was not recorded at the Vermillion Crossing weather station (Smith 2018). It is likely that other factors such as shorter day-length and enhanced night-time recovery of fuel moisture further limited fire growth in September.

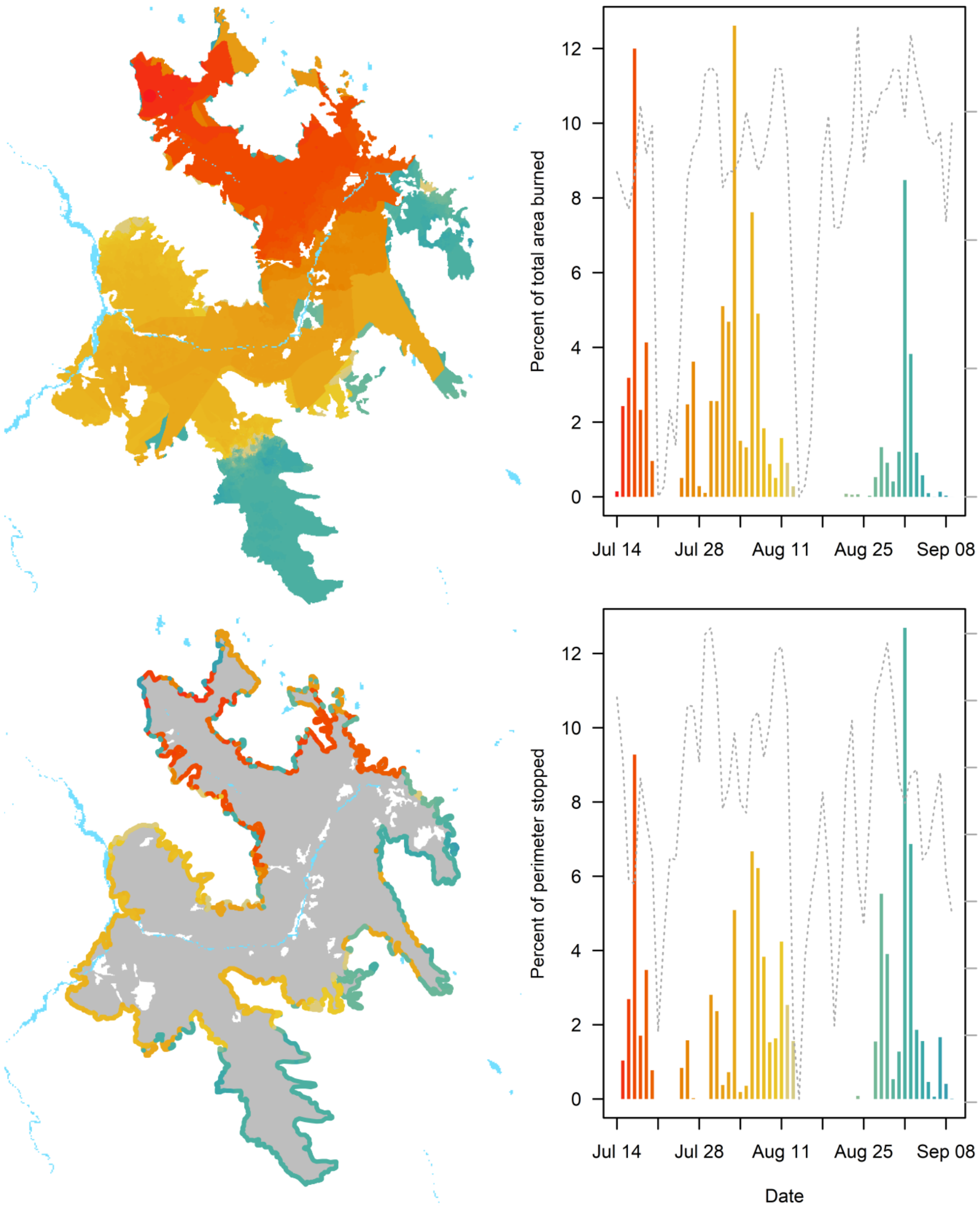

Figure 4: Verdant Creek Fire progression from July 14th - September 8th, 2017. The top section of the figure indicates fire progression, with colours corresponding to daily area burned. The bottom section of the figure indicates the proportion of daily fire perimeter formed, with colours corresponding to the burning date. For visualization, daily changes in the Fire Weather Index (FWI) and Vapor Pressure Deficit (VPD) values are indicated using dotted lines.

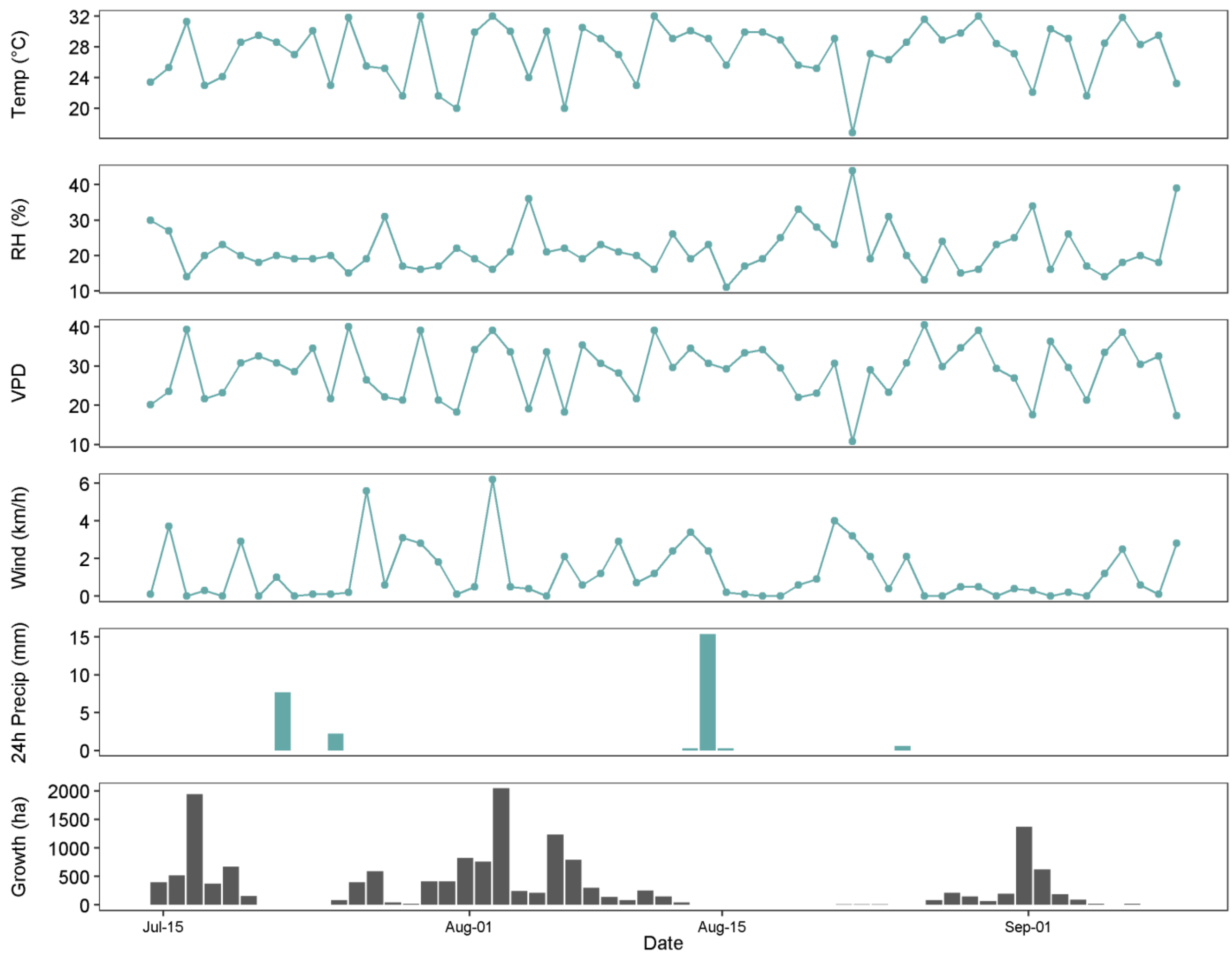

Figure 5: Weather indices from July 14th, the first day of significant fire growth until September 8th, 2017, the last day of any observed fire growth. Weather data is from the Parks Canada Vermillion Crossing Fire Weather Station.

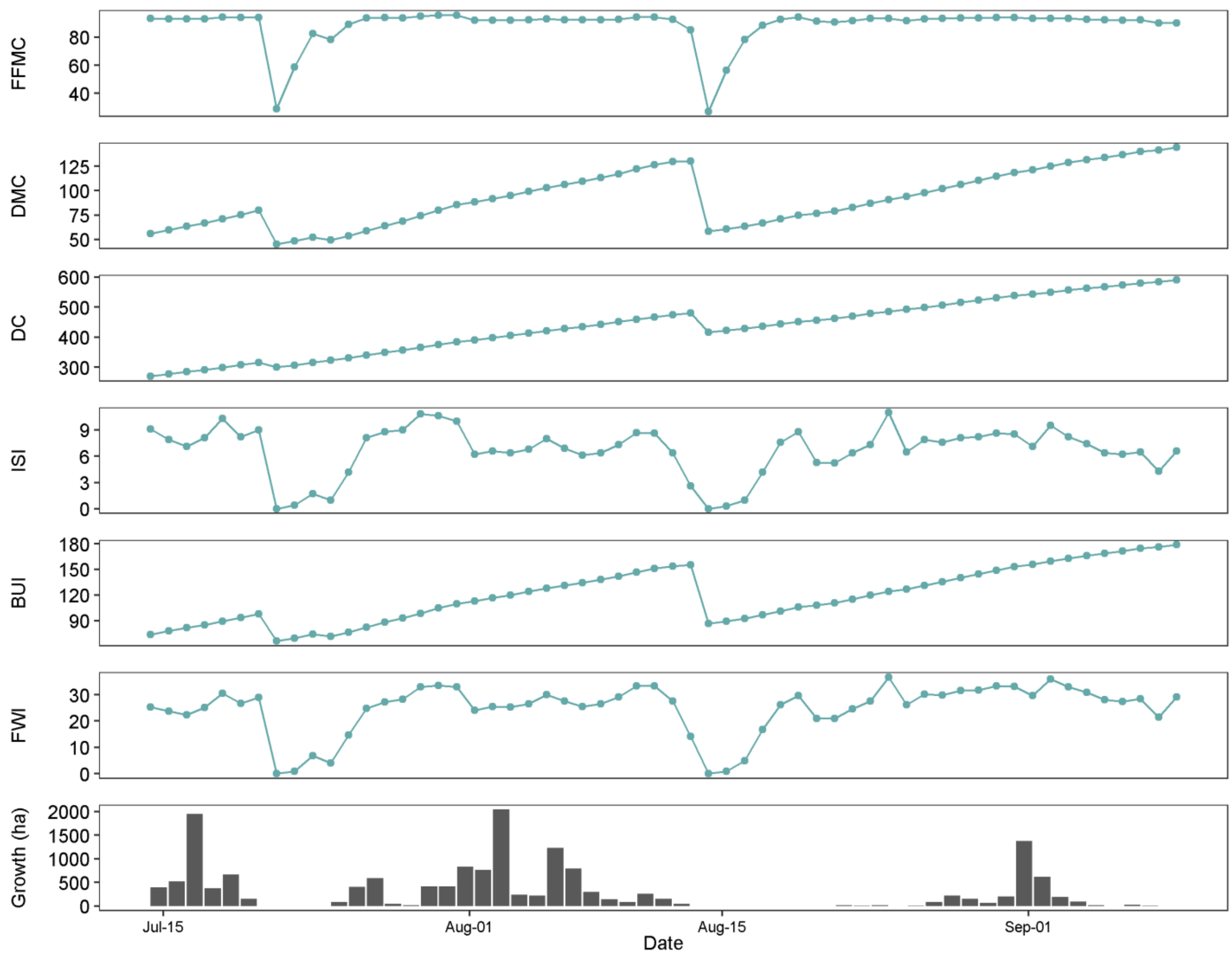

Figure 6: Fire Weather Indexes (FWI) system values from July 14th, the first day of significant fire growth until September 8th, 2017, the last day of any observable fire growth. Data is from the Parks Canada Vermillion Crossing Fire Weather Station.

3.2 Evaluation of Models and the Importance of Variables

3.2.1 Weather Influences

Weather differed significantly between locations where the fire was spreading and locations where the fire had stopped (concordance statistics 0.581-0.736). The 100 m model had a higher predictive ability than the 500 m model at the 1-day time scale (concordance statistic 0.736 and 0.66, respectively). In contrast, the 500 m model had a higher predictive ability than the 100 m model at the 3-day time scale (concordance statistic 0.632 and 0.581, respectively). Overall, the 1-day models were better able to detect differences in weather compared to the 3-day model (Table 3). Of all the models, the 100 m model at the 1-day time scale was best able to detect a difference in weather between unburned and burned locations. Fire cessation tended to occur under lower VPD and FWI values when precipitation occurred.

Table 3: Matched case-control conditional logistic regression (MCC Clogit) analysis to depict fire boundary formation location indicating variables of significance. Variables of significance in models include vapour pressure deficit (VPD), fine fuel moisture code (FFMC), fire weather index (FWI), and wind speed (WDSP) km/h in each model, and the coefficients, standard errors (s.e.) and p-values. P<0.05 '.', P<0.01 '*', P<0.001 '**', P <0.000 '***'.

Case 0 m, -100 m 1-day Removed				*Case 0 m, -100 m 3-day removed*			
Variable	Coefficient	s.e.	P-value	Variable	Coefficient	s.e.	P-value
VPD	-0.17693	0.02707	6.33e-11 ***	VPD	-0.06354	0.01837	0.000542 ***
FWI	0.29955	0.02938	< 2e-16 ***	FFMC	-0.06639	0.02521	0.008443 **
Rain 24 hrs	8.90699	3.84018	0.0204 *	WDSP	-0.12023	0.88672	0.022176 *
Concordance	0.736	0.026		Concordance	0.581	0.03	
Case 0 m, -500 m 1-day Removed				*Case 0 m, -500 m 3-day removed*			
Variable	Coefficient	s.e.	P-value	Variable	Coefficient	s.e.	P-value
VPD	-0.16475	0.02150	1.83e-14 ***	VPD	-0.05177	0.01705	0.00239 **
FWI	0.18799	0.02308	3.78e-16 ***	FFMC	-0.07800	0.02808	0.00547 **
				WDSP	-0.16376	0.05039	0.00116 **
Concordance	0.66	0.028		Concordance	0.632	0.029	

3.2.2 Fuel, Topography, and Anthropogenic Influences

This section highlights the best and worst models that I estimated, as well as several additional models where distances of analysis are similar to those used in previous fire boundary studies

(Table 4). I summarize all model results in the appendix. Fuel and topography differed significantly between burned and unburned locations. Overall, fuel variables had the greatest explanatory value (concordance statistics 0.63-0.87), whereas topography alone resulted in a weak model (concordance statistics 0.58-0.68) (Figure 7). Anthropogenic variables were not significant due to the limited occurrence of roads within the protected area.

Model predictive accuracy was higher for the combined stable fire environment model than the individual topography and fuel models (Figure 7). Predictive accuracy was unacceptably low when attributes at the two most proximate paired points were compared (i.e., -40 m, 40 m; concordance statistic 0.656). The highest predictive accuracy occurred for pairs distant from the fire perimeter (500 m, -500 m; concordance statistic 0.89). The remaining four models summarized in this results section had moderate predictive accuracy (concordance statistics 0.70-0.77). Increasing the distance between burned and unburned locations improved model predictive accuracy.

The distance separating paired sample points influenced the contribution of explanatory variables, as illustrated in the collection of stable fire environment models (Figure 8; Table 5). Fuel conditions were the most consistently influential explanatory variables, with non-fuels, IMAun (Interior Mountain Heather Alpine undefined), FBP C-2 fuel type (Boreal Spruce), sparse horizontal vegetation distribution, and ESSFdkp (Engelman spruce – Subalpine fir dry cool parkland) influencing cessation in more than three models. Of the topographic variables, only distance to waterways influenced fire cessation in more than two models. The remaining variables were not consistently influential across scales of analysis.

Table 4: Summary of distances of analysis highlighted in this result section, all other distances of analysis models are summarized in the appendix. Comparable studies are highlighted for reference; an in-depth analysis of each study is found in Section 1.4 Sample Distances in Previous Studies.

Pairs		
Case	Control	Comparable studies:
0 m	-100 m	O'Connor et al. 2017
0 m	-100 m, -200 m, -300 m, -400 m, -500 m (All)	Narayanaraj and Wimberly 2011
0 m	-500 m	Parks et al. 2015
40 m	-40 m	
100 m	-100 m	
500 m	-500 m	Price et al. 2014

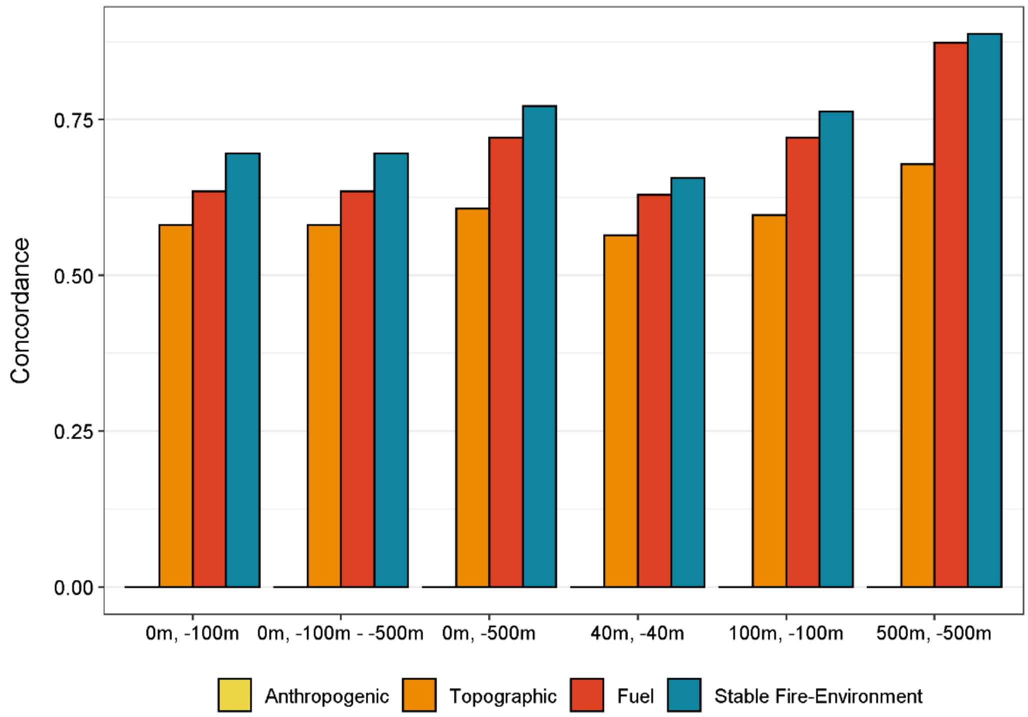

Figure 7: Concordance statistics for the six (Table 4) matched case-control conditional logistic regression (MCC Clogit) models for anthropogenic, topographic, fuel, and the stable fire environment models.

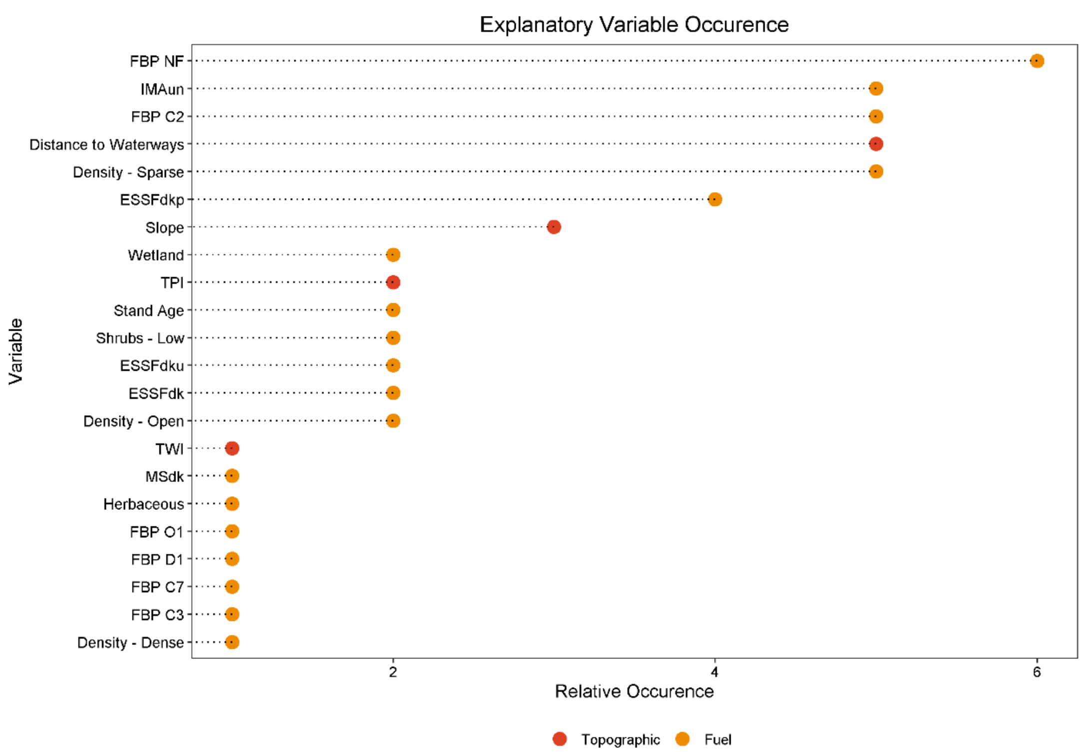

Figure 8: Relative occurrence of explanatory variables for the six fire environment models (Table 4), determined from significant variables in the topographic, fuel, and anthropogenic models.

As would be expected, non-fuels were positively associated with fire boundaries in all models, indicating fire progression tended to stop in areas classified as unvegetated. For five of the models, the C-2 (boreal spruce) fuel type was negatively associated with fire boundaries, indicating the fire progressed through areas classified as dense conifer fuels. Other FBP fuel types were also negatively related to fire boundary formation in at least one model, including C-3 (mature jack or lodgepole pine), C-7 (ponderosa pine – Douglas fir), D-1 (aspen), and O-1 (grass) in which the relationship was relatively weak. These results indicate that fire spread tended to progress through conifer fuel types, but less so through grass fuel types. Of the BEC zones, MSdk (Montane Spruce dry cool), ESSFdk (Engelman Spruce – Subalpine Fir dry cool), and ESSFdkw (Engelman Spruce – Subalpine Fir dry cool woodland) were negatively associated with fire boundaries, indicating fire did not tend to arrest in vegetation associated with valleys. Fire boundaries were positively associated with ESSFdku (Engelman Spruce – Subalpine Fir dry cool undifferentiated), ESSFdkp (Engelman Spruce – Subalpine Fir dry cool parkland), and especially with IMAun (Interior Mountain Heather Alpine undefined). The relationship to these BEC zones indicates fire tended to stop in sub-alpine vegetation but were most likely to stop in alpine vegetation.

Wetland vegetation was positively associated with fire boundaries, indicating fires tended to stop in riparian areas, bogs, fens, marshes, or wetland areas. Fire boundaries were positively associated with low shrubs, which, when validated in orthophotos, aligned with avalanche paths, riparian areas, and particular alpine vegetation. Fire boundaries were negatively associated with increasing stand-age and were negatively associated with herbaceous vegetation, which mainly defined areas burned in 2001 and 2003. Combined, these results indicate that fire boundaries tended to form in younger stands but were unlikely to form in specific post-fire revegetation composed of downed tree boles, grasses, and lodgepole pine saplings. Fire boundaries were negatively associated with horizontally continuous vegetation, indicating fire was unlikely to stop if fuel continuity was greater than 25%. Sparse fuels had an inconsistent relationship with fire boundaries, which was positive in three models and negative in two others. The type, composition, and horizontal distribution of vegetation influenced the probability of fire cessation.

Distance from waterways was negatively associated with fire boundary formation, indicating fires tended to stop near waterways. An increasing slope and absolute TPI were both negatively associated with fire boundary formation, indicating fire spread tended to arrest mid-slope or in areas of moderate topographic complexity rather than steep valley bottoms or ridges. Additionally, a negative association with TWI indicates that fire boundaries tended to form in areas of decreased potential for water pooling.

There were only two clinically significant interactions among explanatory variables, of which none were significant in more than one model. Fire boundaries positively associated with sparse and low shrub areas, but congruent occurrences of these vegetation classifications negatively associated with fire boundaries. These results, combined with orthophoto verification, indicated that fires tended to continue spreading in certain alpine and avalanche vegetation assemblages. ESSFdku (Engelman Spruce – Subalpine Fir dry cool undifferentiated) and increasing stand-age were negatively associated with fire boundary formation, indicating that fire boundaries tended to form in younger ESSFdku stands.

Table 5: Matched Case-Control conditional logistic regression (MCC Clogit) analysis to depict fire boundary formation location indicates variables of significance in sample distance model and the respective coefficients, standard errors (s.e.) and p-values. P<0.05 '.', P<0.01 '*', P<0.001 '**', P <0.000 '***'

Case 40 m, Control -40 m

Variable	Coefficient	s.e.	P-value
River Distance	-5.002914	1.475958	0.000700 ***
Slope	0.024401	0.01001	0.014784 *
FBP C-2	-1.671829	0.472349	0.000401 ***
FBP NF	1.073956	0.239062	7.04e-06 ***
ESSFdk	-0.74469	0.274097	0.006590 **
ESSFdkw	-1.026089	0.378778	0.006750 **
Wetland	2.40499	1.051012	0.022122 *
Sparse	-0.588803	0.253451	0.020171 *
Open	-1.582656	0.243266	7.72e-11 ***

Case 0 Control -100 m

Variable	Coefficient	s.e.	P-value
River Distance	-7.3006909	1.64958	9.61e-06 ***
FBP C-2	-1.1956072	0.544676	0.028158 *
FBP NF	1.7654908	0.391244	6.41e-06 ***
ESSFdkp	1.5288932	0.741778	0.039292 *
IMAun	2.3452085	1.117366	0.035828 *
Shrub Low	1.2669285	0.379859	0.000852 ***
Open	-1.0687081	0.353445	0.002497 **

Case 100, Control -100

Variable	Coefficient	s.e.	P-value
River Distance	-3.77305	1.11059	0.000680 ***
FBP C-2	-1.01395	0.48511	0.036605 *
FBP D-1	-0.76604	0.3563	0.031558 *
FBP NF	2.48984	0.43124	7.76e-09 ***
ESSFdkp	2.17007	0.69565	0.001812 **
IMAun	2.7712	0.95113	0.003573 **
Wetland	1.80437	0.82629	0.028985 *
Shrub Low	1.71396	0.44738	0.000128 ***
Sparse	1.23868	0.33429	0.000211 ***
Sparse and Low Shrub	-2.28768	0.75549	0.002461 **

Case 0, control -500

Variable	Coefficient	s.e.	P-value
River Distance	-2.773354	0.010203	0.000171 ***
Slope	0.034629	0.73792	0.000689 ***
FBP C-2	-1.359351	0.435908	0.001818 **
FBP C-3	-0.507198	0.227616	0.025861 *
FBP C-7	-1.644926	0.485717	0.000708 ***
FBP NF	2.102401	0.333483	2.89e-10 ***
ESSFdku	1.938938	0.500535	0.000107 ***
IMAun	2.956617	1.206961	0.014300 *
Sparse	1.114907	0.281961	7.68e-05 ***
Dense	0.855923	0.328045	0.009076 **
Age	0.003638	0.001361	0.007495 **

Case 500, control -500

Variable	Coefficient	s.e.	P-value
Slope	0.045984	0.012352	0.000197 ***
TWI	0.083593	0.032078	0.009162 **
TPI	0.153264	0.516411	0.766629
FBP D-1	-2.248527	0.633223	0.000384 ***
FBP NF	2.287882	0.551455	3.34e-05 ***
ESSFdku	3.596972	0.891373	5.45e-05 ***
ESSFdkp	2.051683	0.725813	0.004703 **
IMAun	3.526631	1.174993	0.002687 **
Sparse	1.058688	0.334453	0.001549 **
Age	0.005942	0.001842	0.001254 **
ESSFdku and Age	-0.011733	0.004182	0.005027 **

Case 0, control -100 m-500 m

Variable	Coefficient	s.e.	P-value
River Distance	-3.68633	0.76594	1.49e-06 ***
Slope	0.02251	0.00816	0.005816 **
TPI	0.53898	0.24617	0.028565 *
FBP C-2	-0.95389	0.33444	0.004342 **
FBP O-1	0.80745	0.19597	3.78e-05 ***
FBP NF	1.80669	0.24568	1.92e-13 ***
ESSFdkp	1.25175	0.35549	0.000430 ***
ESSFdk	-1.15738	0.22899	4.32e-07 ***
MSdk	-1.53332	0.63029	0.014986 *
IMAun	2.23091	0.54877	4.80e-05 ***
Herbacious	-2.11241	0.67371	0.001716 **
Sparse	0.66092	0.19828	0.859

3.3 Spatial Comparison of Stable Fire Environment Models

Probability maps indicated that identified locations of potential fire boundary formation responded to the stable fire environment and the sample distance (Figure 9). All models predicted that fire boundaries would form in non-fuel and alpine vegetation, while burned areas were most likely to occur in conifer fuels in valleys. Areas of moderate probability were associated with a range of variables, including distance to waterways, TPI, TWI, vegetation composition, and fuel distribution.

Across all models, the proportion of correctly classified burned, perimeter, and unburned sample points varied from 0% to 100% (Table 6). Models that achieved lower predictive accuracy (concordance statistics), correctly classified more burned and unburned sample points. Models with matched pairs near the fire perimeter correctly classified burned areas but had reduced ability to classify unburned locations, trading specificity for sensitivity at this sample distance. Whereas models with pairs distant from the fire perimeter correctly classified all unburned locations but had reduced capability to classify burned locations correctly, trading sensitivity for specificity at this sample distance. The exception was the 100 m, -100 m, which correctly classified 57-70% of all burned, unburned and perimeter locations and achieved a balance of sensitivity and specificity of 72% and 61%, respectively.

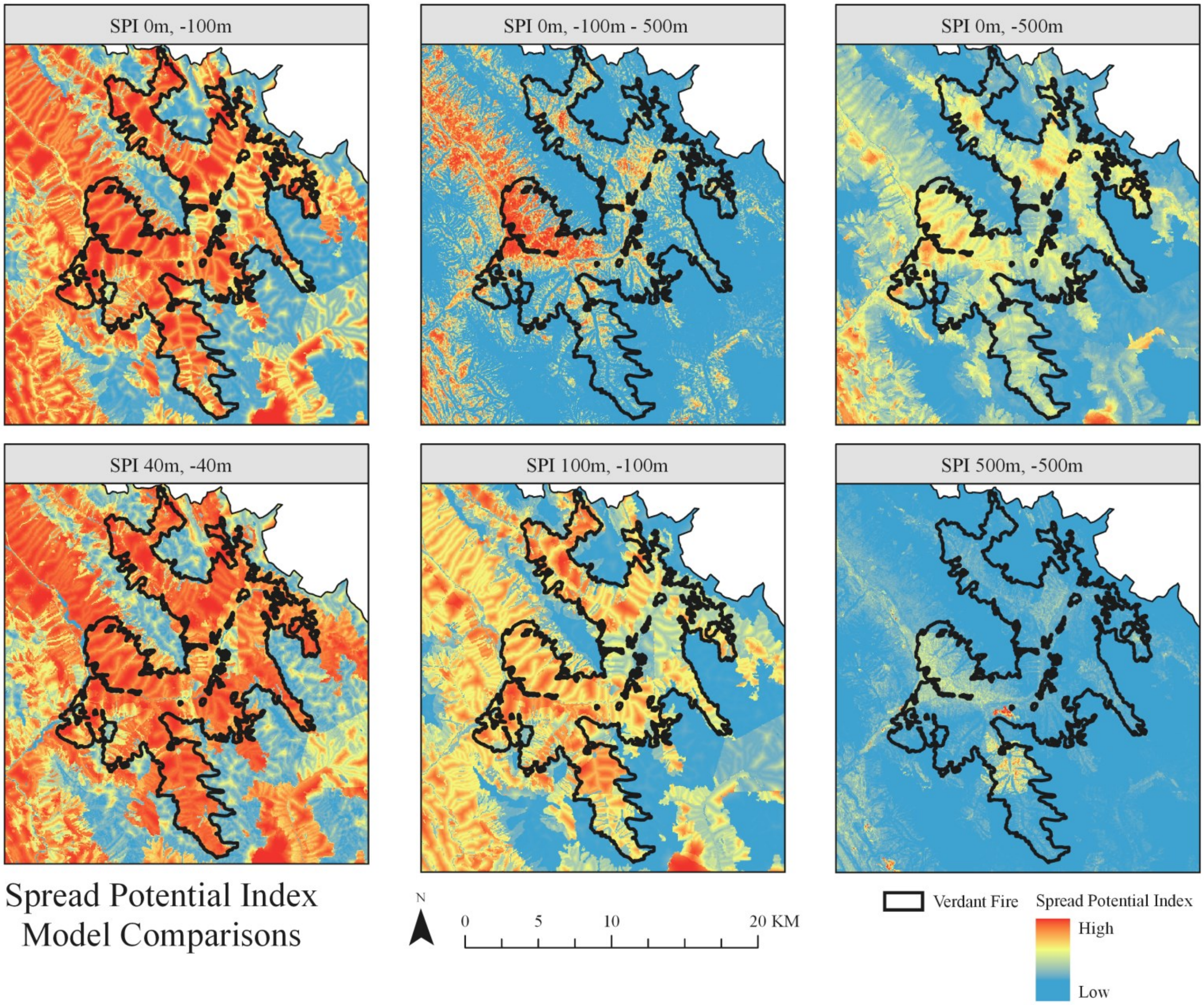

Figure 9: Variability of Spread Potential Index (SPI) depending on the scale of analysis used in the model building process.

Table 6: Model classification accuracy for all sample points inside and outside the fire perimeter. The table indicates each model's ability to classify burned, perimeter, and unburned points correctly.

Pairs		Mean Probability Unburned	Correct					Sensitivity (%)	Specificity (%)
Case	Control		Burned (%)	Perimeter (%)	Unburned (%)	Average (%)	Median (%)		
0 m	-100 m	0.49	76	40	53	56	53	55	76
0 m	All	0.88	15	91	91	65	91	92	15
0 m	-500 m	0.86	8	96	91	66	96	96	8
40 m	-40 m	0.40	86	31	48	55	48	50	86
100 m	-100 m	0.65	61	57	70	63	57	72	61
500 m	-500 m	0.99	0	0	100	33	0	99	0

3.4 Suppression Influence

After removing suppression noise, model predictive accuracy decreased by 0.065 for the weather model (new concordance statistic 0.671) and increased by 0.016 for the stable fire environment model (new concordance statistic 0.779) (Table 7). In the reduced weather model, VPD influence was consistent, FWI influence decreased by 0.12, and precipitation was no longer significant. The inclusion of explanatory variables did not change in the stable fire environment model, although the importance of variables did change. The influence of IMAun (Interior Mountain Heather Alpine undefined) increased by 1.26 and non-fuels by 0.43, while waterway influence decreased by 0.54. Without the influence of fire suppression, fire spread tended to stop in IMAun and non-fuels, while suppression enhanced or selected waterways for boundary formation. Although there were little observable differences when comparing the spatial probability maps with and without the influence of suppression, the sensitivity classification increased, but specificity reduced (Table 8). With or without the influence of suppression, the stable fire environment had a higher predictive accuracy than the weather at understanding the relationship of fire boundary formation.

Table 7: Top two tables compare 100 m, -100 m stable fire environment model with full dataset (left) and areas of anthropogenic influence removed (right). Bottom two tables compare 0 m, -100 m weather model at the 1-day interval with the full dataset(left) and with areas of fire suppression removed(right). Each model reports coefficients, standard errors and p-values. P<0.05 ‘.’, P<0.01 ‘*’, P<0.001 ‘ ** “, P <0.000 “ ***”

Full Dataset

100 m, -100 m stable fire environment model			
Variable	Coefficient	s.e.	P-value
River Distance	-3.77305	1.11059	0.000680 ***
FBP C2	-1.01395	0.48511	0.036605 *
FBP D1	-0.76604	0.3563	0.031558 *
FBP NF	2.48984	0.43124	7.76e-09 ***
ESSFdkp	2.17007	0.69565	0.001812 **
IMAun	2.7712	0.95113	0.003573 **
Wetland	1.80437	0.82629	0.028985 *
Shrub Low	1.71396	0.44738	0.000128 ***
Sparse	1.23868	0.33429	0.000211 ***
Sparse and Low Shrub	-2.28768	0.75549	0.002461 **
Concordance	0.763	0.026	

0 m, -100 m Weather 1-day model			
Variable	Coefficient	s.e.	P-value
VPD	-0.17693	0.02707	6.33e-11 ***
FWI	0.29955	0.02938	< 2e-16 ***
Rain 24 hrs	8.90699	3.84018	0.0204 *
Concordance	0.736	0.026	

Anthropogenic Influence Removed

100 m, -100 m stable fire environment model			
Variable	Coefficient	s.e.	P-value
River Distance	-3.23342	1.17504	0.005928 **
FBP C2	-1.22636	0.51887	0.018101 *
FBP D1	-0.7474	0.36908	0.042863 *
FBP NF	2.92409	0.50551	7.27e-09 ***
ESSFdkp	2.22799	0.7420	0.002694 **
IMAun	4.03794	1.31241	0.002093 **
Wetland	1.85712	0.83270	0.025732 *
Shrub Low	1.93426	0.50482	0.000127 ***
Sparse	1.44342	0.36980	9.49e-05 ***
Sparse and Low Shrub	-2.60089	0.82723	0.001666 **
Concordance	0.779	0.026	

0 m, -100 m Weather 1-day model			
Variable	Coefficient	s.e.	P-value
VPD	-0.18747	0.02529	1.25e-13 ***
FWI	0.18715	0.02459	2.51e-14 ***
Concordance	0.671	0.026	

Table 8: Model classification accuracy for all sample points inside and outside the fire perimeter using the 100 m, -100 m analysis distance. The table indicates each model's ability to classify burned, perimeter, and unburned points correctly. The full model is based on the full dataset, including areas of anthropogenic influence while the reduced model has suppression influence removed.

Data Set	Mean Probability Unubnred	Correct						
		Burned (%)	Perimeter (%)	Unburned (%)	Average (%)	Median (%)	Sensitivity (%)	Specificity (%)
Full	0.65	61	57	70	63	57	72	61
Reduced	0.68	59	60	72	64	60	74	59

Chapter 4 Discussion

In this chapter, a discussion of the interactions between fire environment conditions and fire cessation follows, including: (1) the impact of the sample distance on the predictive ability of fire environment variables for estimating the probability of fire boundary formation; (2) the influence of the fire environment, weather, topography, fuel, and anthropogenic contributions to fire cessation; (3) the potential applications of this work for fire management decision-support.

4.1 Sample Distance

Modellers investigating the formation of fire boundaries must identify paired sample points that are close enough together to represent conditions where the fire stopped but not so close that their distinct status (i.e., burned versus unburned) is compromised. Previous studies did not explicitly address the influence of the distance between matched pairs on model results. Any attempts to compare the influence of sample point separation across studies are inhibited due to each study employing a different analysis method. No consensus exists as to which distance between paired points is most appropriate to capture complex fire-environment interactions leading to fire cessation. My analysis helps elucidate the influence and importance of these spatial scale issues in fire cessation modelling.

For the Verdant Creek Fire, the distance between paired sample points had a profound impact on model performance: predictive ability, sensitivity, and specificity. For models with control locations greater than 100 m from the fire perimeter, predictive ability appeared to have high potential to assess fire cessation; however, the performance of the spatial probability maps to correctly classify unburned areas was poor (specificity 0% to 15%). For these models, the lower half of the probability colour ramp (i.e., cool spots unlikely to be burned) represented much of the landscape. At this broad-scale, each pair of fire perimeter and interior points are significantly different. Still, across the landscape, these differences do not produce nor influence the mechanism and process of fire cessation.

Models with case and control locations within 100 m of the fire perimeter, had the lowest predictive ability. The ability of probability maps to detect burned areas improved (specificity 76% - 86%), but the ability to correctly classify unburned areas decreased (sensitivity 50% and 55%). Errors at these scales of analysis may be due to inherent errors introduced from the dNBR perimeter used in many fire cessation studies (i.e., Narayanaraj and Wimberly 2011; Holsinger et al. 2016; O'Connor et al. 2017). The dNBR method operates at a 30 m resolution and cannot robustly detect low burn severity below tree canopy (Kolden et al. 2012), which may fail to identify and locate a fuzzy fire boundary (McIntire 2004; Povak et al. 2018). As a result, the fire perimeter and subsequently sample points may be incorrectly located within the fire cessation process, obscuring potential differences between the inside and outside of the fire perimeter. Furthermore, the 30 m resolution of VRI data generalizes forest characteristics and obscures small stand discontinuities (Sandvoss et al. 2005) as such fine-scale vegetation characteristics that may be predisposed to fire cessation are masked from the analysis.

The 100 m, -100 m model, performs the best overall with an acceptable predictive ability, and a balanced sensitivity and specificity. This distance of case and control points away from the fire perimeter overcomes potential errors introduced from the dNBR method. Likewise, modelling at this spatial scale may indicate the closest distance at which generalized VRI data can capture meaningful fire-environment differences. These results also support the understandings that fire propagation is dependent on fuels that are receptive to radiant heat transfer and short-range spotting between 30 m – 100 m from the fire front (Alexander et al. 2004; Beverly et al. 2010). This scale of analysis is likely broad enough to capture the differences between burned and unburned areas, such that points are located outside of ecotones, transitional areas, of diminishing intensity and severity (Forman 1995). The high performance of this sample distance progresses an understanding that fire boundaries are not a discrete event, but rather a belt of diminishing fire intensity, as was observed in south-central British Columbia where fire cessation occurred between 0 m – 127 m (McIntire and Fortin 2006).

As in most model building exercises, there is a tendency to strive for models with high predictive performance; however, caution is required in accepting unvalidated models. My work suggests that sampling within 100 m, or on, the fire perimeter should be avoided due to the potential to locate sample points within the fire cessation process, such that they are not independent of the process. The location of points within the perceived process results from the transitional gradient of fire cessation and the spatial resolution of data available in this study. Studies using data that capture the landscape at a finer spatial scale may be able to locate points nearer to the fire perimeter. Sampling at too distant a scale from the fire perimeter can be expected to increase the statistical significance of models, given the limited influence of spatial autocorrelation, resulting in the models failing to capture essential characteristics and relationships that affect fire boundary formation. Further analysis will be required to determine if this sampling distance is appropriate for other fires in the Canadian Rocky Mountains. Likewise, these results may not hold in other ecoregions, where fire cessation may occur over different spatial extents.

4.2 Fire Environment and Fire Cessation

The fire environment is a recognized driver of fire propagation (Countryman 1972). In the northern American Rocky Mountains, Holsinger et al. (2016) demonstrated that weather, fuel, and to a limited extent topography, influenced fire cessation. My analysis supports that weather, fuels, topography, and suppression influence the fire cessation process in the western Canadian Rocky Mountains.

4.2.1 Weather

Weather is a significant component of the fire environment, influencing fire behaviour, rates of spread, and fire cessation in the northern Rocky Mountains (Fryer and Johnson 1988; Holsinger et al. 2016). My analysis indicates that a down-turn in fire weather was informative for detecting conditions conducive to fire cessation. Precipitation in the previous 24-hours was highly influential for fire cessation supporting the findings of Latham and Rothermel (1993) that fires may burn for weeks or months until a significant precipitation event. The next most influential variable was VPD, which accounts for the difference between temperature and relative humidity (Lawrence 2005) and affects vegetation susceptibility to ignition (Sedano and Randerson 2014; Seager et al. 2015). Findings on VPD corroborate research in the southern United States and Alaska, where higher VPDs are associated with fire growth and lower values with fire cessation (Sedano and Randerson 2014; Just et al. 2016). The final most influential variable was FWI, a relative rating of fireline intensity, which reflects both rates of spread and fuel consumption (Van Wagner 1987). Higher FWI values are attributed to fire growth across Canada (Flannigan et al. 2005; Podur and Wotton 2011; Parisien et al. 2014), while lower FWI values are associated with fire refugia formation in western Canada (Krawchuk et al. 2016).

Although the weather model indicates an ability to detect fire cessation, the model has limitations. The single weather station used in the analysis does not capture the complete range of weather experienced across the fire. Future studies may benefit by using all nearby weather stations to create a landscape of gridded weather to account for microclimate variations (Horel et al. 2014) and relate these values to the sample points. Although this interpolation approach would increase the spatial accuracy of data, it would continue to limit results to a broad temporal scale. To further enhance weather models, the date of burning would need to be refined to the hour of burning and extinguishment (Holsinger et al. 2016). The required temporal scale is not available with the current MODIS/VIIRS fire detection solutions.

4.2.2 Topography

The results of this study suggest that waterways contribute to fire cessation. Streams and rivers generate cool, moist, and shady microclimates, facilitating the growth of vegetative assemblages with higher fuel moisture contents, while the waterway itself disrupts the continuity of fuels (Agee 1993). Waterways naturally function as fire barriers due to their fuel composition and microclimates (Dwire and Kauffman 2003, and references contained therein), while the ready access to water provides ideal locations for firefighting. My results are contrary to those of Narayanaraj and Wimberly (2011), who reported that fire boundaries did not associate with rivers and streams in the Cascade Mountains of Washington. In that study, ridgelines were found to dominate fire boundary processes, which may have obscured the influence of waterways. The discrepancy may also occur if the fires Narayanaraj and Wimberly (2011), varied in seasonality or influence of drought, or if the data used omitted ephemeral streams, which were included in the present study. By including smaller waterways, my results are likely capturing how streams, running perpendicular to ridgelines, limit horizontal fire spread in the Canadian Rocky Mountains (Suffling 1993).

No other topographic variables were significant for predicting fire cessation in the best model. These results are surprising given that topography was influential for arresting fire spread in the Foothills of Alberta, southern United States and, to a lesser extent, the northern United States (Narayanaraj and Wimberly 2011; Andison 2012; Holsinger et al. 2016; Povak et al. 2018). These results, however, support a northward diminishment of topographic influence on the fire cessation process in the Rocky Mountains. Results of this study are consistent with evidence that fire refugia in western Canada are more likely to form under moderate to benign fire weather conditions (FWI < 29), and in locations with moderate topographic complexity (Ferster et al. 2016; Krawchuk et al. 2016). As few days of benign to moderate fire weather occurred during the Verdant Creek Fire, the extreme fire weather that dominated likely diminished any potential influences of topography. Similarly, during the Yellowstone fires of 1988, extreme drought conditions allowed fire to propagate across formidable barriers to fire spread, including large canyons (Turner et al. 1994).

4.2.3 Fuel

In terms of the influence of specific fuel variables on fire cessation, the BEC IMAun (Interior Mountain Heather Alpine undefined) was the most highly influential, followed closely by the British Columbia classification of non-fuel areas, then ESSFdkp (Engelman Spruce – Subalpine Fir dry cool parkland). The influence of the IMAun and ESSFdkp supports the understanding that in southeastern British Columbia, there is little to no occurrence of fire in these forest types (Marcoux 2008). Yet, the increasing influence from the transitional parkland area into the alpine, suggests that the intermediate ESSFdkp fuel complex can support a fire spreading through tree clumps in a matrix of alpine meadows. This phenomenon was observed when the Verdant Creek Fire spread through the Continental Divide region, where strong winds propelled firebrands and supported fire propagation through alpine and parkland areas (Smith 2018). Non-fuels were, unsurprisingly, influential in fire boundary formation; however, they were less influential than the IMAun. This may indicate that areas classified as non-fuels by the Province of British Columbia may sometimes contain areas available for fire consumption. Fire cessation was less likely to occur in the FBP C-2 (boreal spruce) fuel type than the D-1/2 (aspen) fuel type, corroborating general differences in predicted fire spread rates for these two fuel types (Taylor & Alexander, 2016).

My results indicate that fires were more likely to stop in wetland and avalanche vegetation consisting of sparse and low shrubs. This relationship between wetlands and fire cessation is consistent with findings reported by Just et al. (2016) for a study area in North Carolina, where microclimates and vegetation observed in wetland areas limited fire spread. In the Rocky Mountains of southern Alberta, avalanche paths, which extended from the alpine to valley bottoms intersected with wetlands or streams, stopped fires; however, if fire spread is being driven by embers transported aloft and ahead of the fire, it is thought that multiple sequential avalanche paths would be necessary to arrest fire growth (Suffling 1993).

Horizontal fuel continuity increases rates of fire spread by enabling faster preheating of proximate fuels (Brown 1981). Results indicated that sparse vegetation (i.e., 10-25% fuel continuity) had a positive influence on the formation of the fire boundary; however, the relationship was inconsistent across models, suggesting a complex connection with fire cessation. Increasing crown closure was found to be associated with increased fire behaviour in the Cascade Mountains of Washington (Prichard et al. 2017); however, there was no detectable relationship between crown closure and fire boundary formation on the Verdant Creek Fire. It is possible that fire behaviour will increase with crown closure until a threshold beyond which fire behaviour decreases (Bilgili 2003), possibly due to obstruction of incoming solar radiation and in-stand airflow, inhibiting understory vegetation growth, fuel drying, and fire spread (Albini and Baughman 1979; Wotton and Beverly 2007). These inconsistencies may indicate a gradient of influence, an artifact of distances of analysis, or imagery classification errors.

Contrary to results found in the southern United States (i.e., Holsinger et al. 2016; Parks et al. 2016), there was no detectable relationship between regenerating vegetation from past fires and fire cessation. The Verdant Creek Fire burned through fires from 1991, 1994, and considerable portions of fires from 2001 and 2012. Although the Verdant Creek Fire did not stop at the perimeters of these past burns, as often occurs in the Canadian boreal forest (Amiro et al. 2001), the fire did stop within more recent burns (2001 and 2012 fires). Likewise, during the extreme drought and fire season of 2003 in KNP, fires spread into previously burned areas but exhibited diminished spread rates and burn severity (Stevens-Rumann et al. 2016). This relationship supports understandings from the northern United States, where Holsinger et al. (2016) reported that past fires had little influence on fire cessation beyond five years and that extreme drought diminishes the protective effects of past fires (Parks et al. 2016). Likewise, in the foothills of Alberta, stand age had no detectable relation to fire cessation or refugia formation (Andison 2012). In this study, results support understandings that past fires in the Canadian Rocky Mountains are not-self limiting but rather self-regulating and present enhanced opportunities for fire management

(Stevens-Rumann et al. 2016), which is consistent with prior studies of self-regulating fire effects in the northern United States (i.e., Parks et al. 2014).

The use of VRI data and derived FBP System fuel type maps (Perrakis et al. 2018) introduces potential data inaccuracies. VRI classification is derived from mid-scale aerial photographs with limited ground-truthing, which are used to model and estimate stand characteristics (Sandvoss et al. 2005); however, Kubian (2013) reported that estimated VRI stand age in KNP was satisfactory using tree rings collected during field visits. VRI provides a province-wide inventory of forest cover, which is likely to improve with time as newer images, ground-truthing, and enhanced inventory practices are incorporated.

4.2.4 Anthropogenic

Distance to roads was not an influential factor for arresting fire spread. This is contrary to findings in the western United States and Australia, where distances to roads positively influenced fire boundary formation due to their ability to function as conduits for firefighting resources and control locations (Narayanaraj and Wimberly 2011; Price et al. 2014; O'Connor et al. 2017). The lack of association between roads and fire cessation in this study likely reflects the fact that the main roadway through the park, Highway 93 South, parallels the Vermillion River, which effectively separated the highway from the fire edge. Although the highway was used to transport resources to and from the fire, the presence of the highway in proximity to the fire was not a significant factor in the formation of the fire boundary at the distances analyzed.

Fire cessation studies have been conducted in wilderness areas, parkland, and intensively managed areas, where the influence of fire suppression can range from minimal to extensive (Narayanaraj and Wimberly 2011; Price et al. 2014; O'Connor et al. 2017); however, in most cases the exact locations of suppression are unknown. I followed the standard approach used in prior fire cessation studies and grouped managed and unmanaged areas of the Verdant Creek Fire together for analysis. My personal knowledge of fire behaviour and the locations of fire suppression interventions (Smith 2018) allowed me to detect and remove data points that were likely influenced by the confounding effects of fire suppression on fire boundary formation. When modelling was restricted to the unsuppressed edges of the fire, weather was significantly less influential in fire cessation. The influence of VPD and FWI also decreased, and the influence of 24-hour precipitation was no longer effective for predicting fire cessation. In Canada, periods of cooler temperatures and higher relative humidities are known to limit fire spread; however, even when these conditions persist for multiple days, a return to favourable weather can quickly result in a resumption of fire spread (Wang et al. 2014). Such that downturns in fire weather provide the opportunity for fire suppression to be successful and make use of areas of reduced spread potential. In the United States, suppression action often occurs during periods of reduced fire-weather (Finney et al. 2009). Control lines established by fire suppression campaigns are a critical component of fire management, but the ability to contain fire effectively is ultimately influenced by fire weather and behaviour (Mees and Strauss 1992; Hirsch and Martell 1996; Dunn et al. 2017a).

Without the confounding effects of fire suppression, the stable fire environment variables became more influential to fire cessation. The decreased influence of waterways for fire boundary formation suggests that fire suppression takes advantage of areas that naturally diminish fire spread. Waterways likely have a similar influence to that of roads with respect to suppression (Narayanaraj and Wimberly 2011), as they function as conduits for fire fighting resources and successful control locations due to ready access to water in the Canadian Rocky Mountains. The increased influence of non-fuels and IMAun (Interior Mountain Heather Alpine undefined) suggests that these areas are not selected for the application of fire suppression tactics. Overall, the relationship of the stable fire-environment variables to fire cessation remained unchanged, despite the removal of fire suppression influences.

4.2.5 Fire Environment Synthesis

Similar to studies in the northwestern United States (Holsinger et al. 2016), fire cessation was predominately influenced by vegetation and, to a much lesser extent, topography. The significant drought during 2017 may have acted as a top-down influence, overriding the potential bottom-up influences of topography. Although weather was influential to fire cessation, the weather model had a lower predictive ability than the stable fire environment model. The stable fire environment model was able to predict burned and unburned locations around the fire perimeter with 63% accuracy. In comparison, in the northern Rocky Mountains of the United States, O'Connor et al. (2017) used a similar sample distance (0 m, -100 m) and topography, vegetation, and suppression metrics to produce a model with 69% accuracy. Although weather may influence the success of suppression activities, weather contributions to fire cessation in unmanaged areas of the Verdant Creek Fire were limited. The findings of this study indicate the use of MCC Clogit, a relatively new analytical approach, is well suited for detecting the influences of the fire environment on fire cessation in the Canadian Rocky Mountains.

4.3 Relevance to Fire Management

Implications of these results for fire management depend on the expectations that managers have about fire boundary predictions and how these predictions are then used to inform decisions and actions. Fire cessation studies are one means to better-understand fire behaviour. Fire management agencies often use dynamic fire behaviour characteristics (weather, and suppression effectiveness) to inform management decisions and objectives; however, these are often opportunistic in nature and form part of the operational planning window of hours to days (Latham and Rothermel 1993; McIntire 2004; Calkin et al. 2011; Wang et al. 2014). The stable characteristics of the fire environment (fuels, topography, and anthropogenic influences) present management opportunities suited to both reactive and proactive strategic planning.

Previous studies (i.e. O'Connor et al. 2016, 2017) promoted the use of spatial probability maps in proactive and reactive decision making by identifying control locations based on estimated suppression difficulty. When comparing the final fire perimeter to the spatial probability map for the Verdant Creek Fire, there are many potential locations where the fire had a higher probability of cessation but did not stop. I propose that spatial probability maps are not modelling the exact locations where fire will stop but are instead capturing the spread potential dependent on appropriate fire diminishing weather. On their own, many fire managers may intuitively identify fire environment factors and their relationship to fire spread. The proposed SPI allows for rapid visual assessment of complex interactions between the fire-environment and the influence on fire spread and cessation (Figure 10). In proactive management, areas of high spread potential near values at risk could be identified for fuel management and have vegetative characteristics modified in GIS to assess if a proposed treatment would substantially lower the SPI. In reactive management, areas of lower SPI could be targeted for suppression efforts if conducive weather occurs and could be further combined with the maps of potential control locations (O'Connor et al. 2017). Likewise, by incorporating an understanding of SPI and locations likely to form boundaries to fire spread, there is potential to increase the accuracy of fire propagation models

(Alexander et al. 2004). However, before any widespread promotion of this method in decision support systems, systematic efforts to evaluate the effectiveness of the maps are required. In response, fine-scale definitive activities should be approached with caution and consideration until thoroughly investigated.

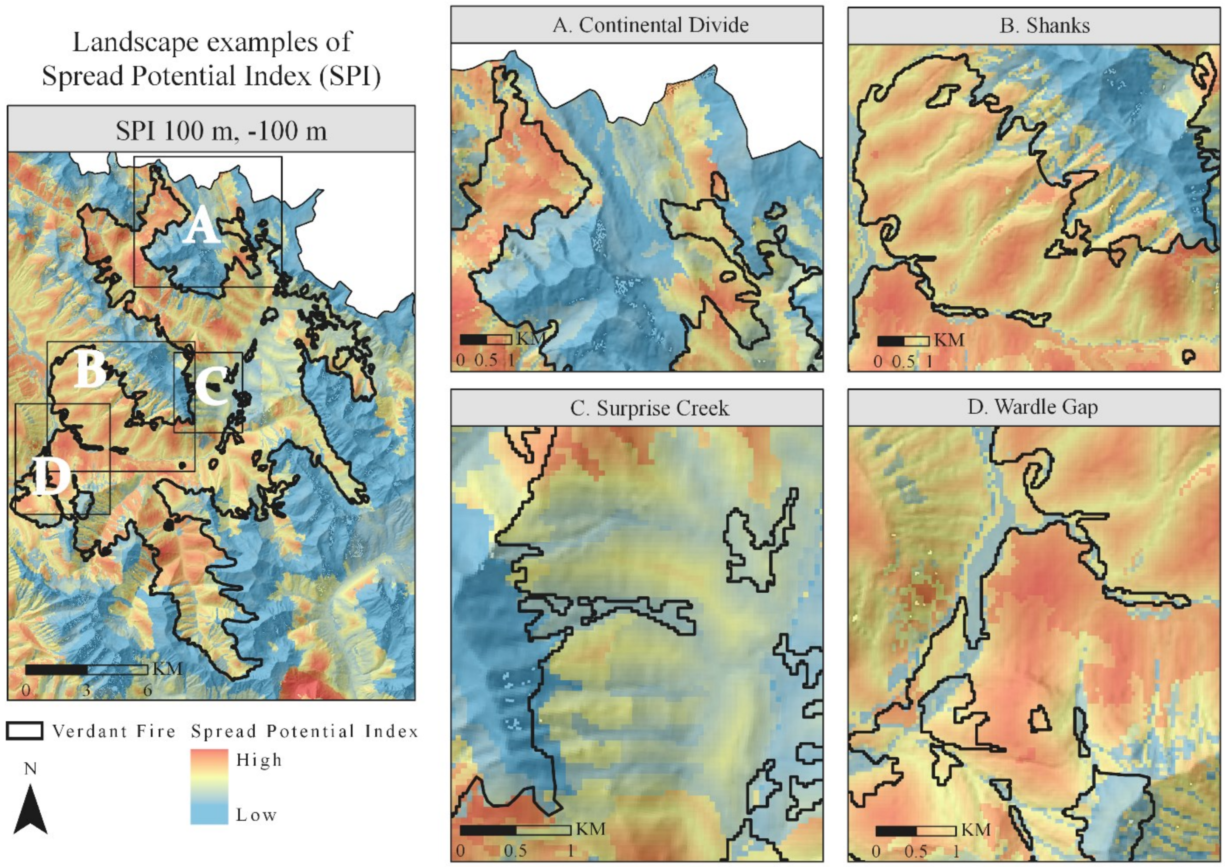

Figure 10: Spread Potential Index (SPI) using the best fire environment model (100 m, -100 m analysis distance). SPI may be used to identify potential containment areas or areas which pose a significant chance of rapid spread (A-D).

4.4 Future Research

In this thesis, I applied relatively new statistical analysis methods to model fire cessation processes in an understudied landscape. The Canadian Rocky Mountain ecoregion represented by the Verdant Creek case-study fire used in this research proved suitable for matched case-control conditional logistic regression modelling of fire boundary formation; however, further analysis of fire boundaries in other important Canadian ecosystems such as the boreal forest will be necessary to fully explore the extent to which relationships between fire environment variables and fire cessation processes vary geographically. Future work could address potential errors introduced from the dNBR method used in this study and VRI inaccuracies while incorporating perimeters that formed under various weather conditions (O'Connor et al. 2017). By performing analysis on a broader temporal and spatial selection of fires with varying weather conditions, one will be better able to understand the full relationship between the fire-environment and fire-cessation. Before accepting a sample distance to be used in analysis, future research would benefit from field validation fire cessation process distance (McIntire and Fortin 2006).

There are no existing models for decelerating fire spread or fire cessation (Alexander et al. 2004; Tymstra et al. 2010). SPI is a new fire environment attribute that could be further studied to inform advances in fire growth modelling (Davis et al. 2010). Future research will also be needed to better understand the relationship of the SPI to daily fire growth and ways to incorporate interactions with weather into fire behaviour modelling.

Chapter 5 Conclusion

The stable fire environment, fuel and topography, were critical determinants of where the 2017 Verdant Creek Fire in Kootenay National Park was observed to stop. Fire suppression was effective during concurrent diminishing fire weather. The magnitude of the distance between burned and unburned locations was an important determinant of model results. Overall, comparing sample locations 100 m inside the fire perimeter to sample locations 100 m outside the fire perimeter resulted in the most robust model performance to detect the relatively fine-scale process of fire cessation. Although many of the results of this study may be intuitive to fire managers, the probability surface showing landscape areas of overlapping influence allows for rapid visual assessment. The Spread Potential Index (SPI) map derived from the stable fire-environment probability map provides a relative rating burning potential under favourable fire weather. These results are only considered applicable for a small area of Kootenay National Park, and any further extrapolations must incorporate other fires from the Canadian Rocky Mountain ecoregion. Inclusion of fire cessation studies and SPI into fire behaviour prediction could provide further understandings of the extent of fires across ecoregions.

My results support the use of fire cessation studies to inform fire management. As this is an evolving area of study, practical use of results to determine localized actions should proceed with caution. This research is one of a handful of assessments that have applied a relatively new technique to understand fire cessation and provides the only evaluation focusing on the influence of spatial scale of analysis. My research supports a developing understanding that the importance of the fire-environment on fire cessation varies by ecoregion.

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Appendix

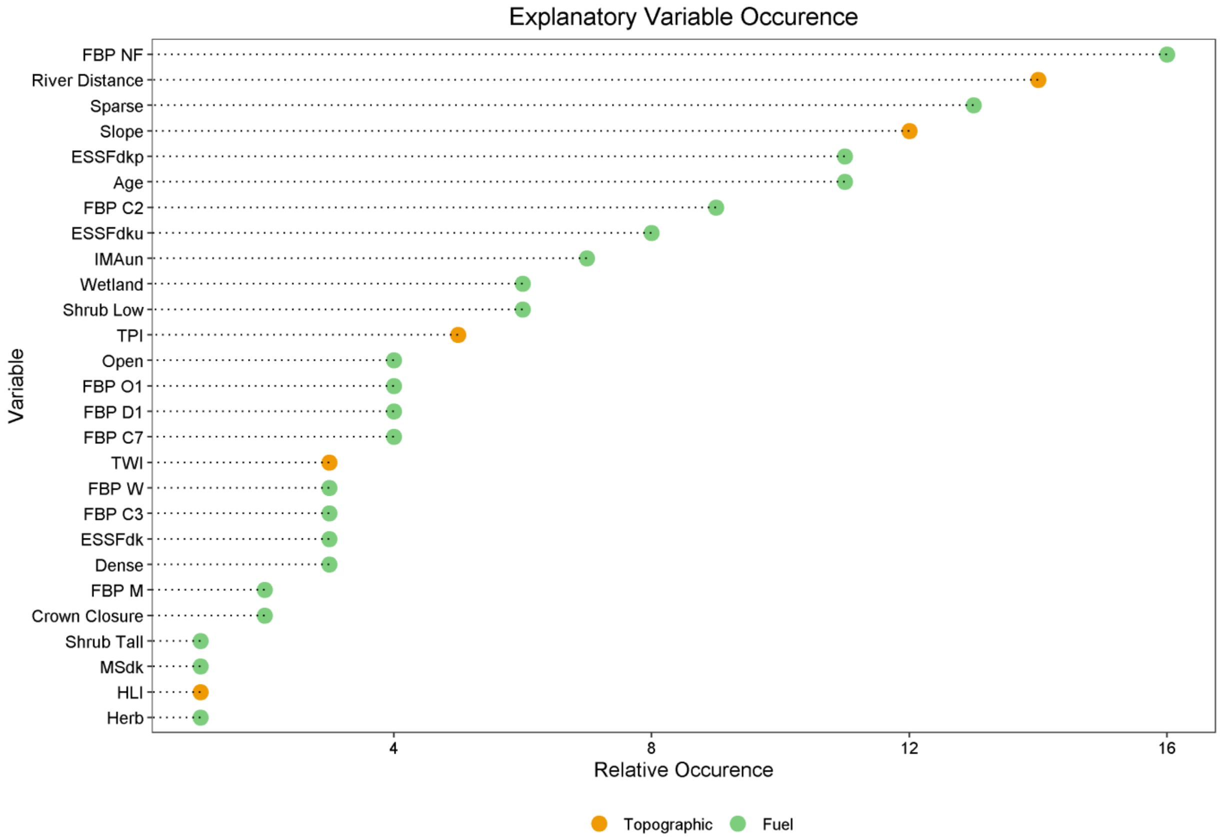

Figure 11: Relative occurrence of variables for all final fire-environment models (16 distances of analysis)

Table 9: Matched Case-Control Logistic regression models for each paired grouping, indicating fuel, topography, and full fire environment models. Classification accuracy for models was further assessed using the model's ability to classify all available correctly

Unburned Pairs		Concordance				Burned		Perimeter		Unburned			
Case	Control	Fuel	Topography	Full	Mean Probability Unubnred	Correct (%)	Incorrect (%)	Correct (%)	Incorrect (%)	Correct (%)	Incorrect (%)	Sensitivity (%)	Specificity (%)
100 m	-100 m	0.721	0.597	0.763	35	61	40	57	43	70	30	72	61
100 m	-200 m	0.759	0.602	0.801	13	8	91	96	4	98	2	98	8
100 m	-300 m	0.769	0.608	0.808	9	2	98	99	1	99	1	99	2
100 m	-400 m	0.808	0.631	0.842	1	1	99	100	0	100	0	13	1
100 m	-500 m	0.819	0.631	0.869	6	3	97	99	1	99	1	1	7

Perimeter Pairs		Concordance				Burned		Perimeter		Unburned			
Case	Control	Fuel	Topography	Full	Mean Probability Unubnred	Correct (%)	Incorrect (%)	Correct (%)	Incorrect (%)	Correct (%)	Incorrect (%)	Sensitivity (%)	Specificity (%)
0 m	-100 m	0.635	0.581	0.696	51	76	24	40	60	53	47	55	76
0 m	-200 m	0.642	0.562	0.678	47	77	23	41	59	54	46	56	77
0 m	-300 m	0.688	0.571	0.728	2	1	99	100	0	100	0	99	0
0 m	-400 m	0.709	0.623	0.762	14	9	91	96	4	95	5	96	9
0 m	-500 m	0.721	0.607	0.772	14	8	91	96	3	96	4	96	9
0 m	All	0.689	0.594	0.746	12	15	85	91	9	91	9	92	15

Equidistant Pairs		Concordance				Burned		Perimeter		Unburned			
Case	Control	Fuel	Topography	Full	Mean Probability Unubnred	Correct (%)	Incorrect (%)	Correct (%)	Case	Control	Fuel	Topography	Full
40 m	-40 m	0.629	0.564	0.656	60	86	14	31	69	48	52	51	86
100 m	-100 m	0.721	0.597	0.763	35	61	40	57	43	70	30	72	61
200 m	-200 m	0.811	0.604	0.834	25	35	65	77	23	86	15	87	35
300 m	-300 m	0.834	0.601	0.839	0	0	100	100	0	100	0	100	0
400 m	-400 m	0.87	0.661	0.904	1	0	100	100	0	100	0	100	0
500 m	-500 m	0.873	0.678	0.887	1%	0%	100%	100%	0%	100%	0%	100%	0%

Table 10: Comparisons of 100 m model compared to increasing spatial scales into the fire perimeter

Model	100 m, -100 m		100 m, -200 m		100 m, -300 m		100 m, -400 m		100 m, -500 m	
Concordance and SE	0.763	0.026	0.801	0.024	0.808	0.024	0.842	0.022	0.869	0.021
Variable	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Waterway Distance	-3.7731	0.000680 ***	-3.387	0.000455 ***	-3.0456	0.000155 ***	-3.411717	6.23e-05 ***	-2.2452	0.004623 **
Density - Sparse	1.23868	0.000211 ***	1.39245	4.66e-05 ***	0.94116	0.000295 ***	1.011045	0.000563 ***	1.75875	4.73e-06 ***
ESSFdkp	2.17007	0.001812 **	1.32277	0.026182 *	2.18305	0.000263 ***	1.631505	0.006211 **	2.18614	0.001218 **
FBP NF	2.48984	7.76e-09 ***	3.65323	5.83e-12 ***	2.89079	2.42e-15 ***	2.979413	3.25e-12 ***	2.03206	4.14e-05 ***
Shrub - Low	1.71396	0.000128 ***	2.25191	2.06e-07 ***					1.02076	0.002167 **
Sparse and Low Shrub	-2.2877	0.002461 **	-2.3819	0.001871 **					-1.8597	0.005153 **
IMAun	2.7712	0.003573 **	2.05643	0.011507 *					4.04183	0.000420 ***
FBP C2	-1.014	0.036605 *					-2.742072	3.17e-05 ***	-1.1167	0.039086 *
Wetland	1.80437	0.028985 *					5.159125	6.48e-05 ***	1.5034	0.048469 *
FBP D1	-0.766	0.031558 *								
Shrub - Tall			1.72885	0.031720 *						
FBP C3			0.68118	0.023144 *						
FBP Water			2.48268	0.021994 *	2.60157	0.014080 *				
Stand Age			0.0033	0.040509 *	0.00496	0.001866 **	0.007602	0.000292 ***	0.00739	0.000147 ***
Slope			0.02046	0.086898 .	0.02941	0.004147 **	0.040818	0.000397 ***	0.04023	0.000476 ***
ESSFdku					1.34697	0.003252 **	4.276663	2.57e-06 ***	5.23237	5.95e-07 ***
ESSFdku and Grass					1.38495	0.012827 *				
FBP 01AB					0.57317	0.065300 .				
Denisty - Dense							-1.025438	0.210879		
Dense and Age							0.01633	0.001418 **		
HLI							3.033189	0.041580 *		
FBP M							-2.266692	0.091394 .	-2.538	0.035476 *
ESSFdku and age							-0.015178	0.000546 ***	-0.0169	0.000665 ***
TWI									-0.006	0.806641

Table 11: Comparisons of 0 m model compared to increasing spatial scales into the fire perimeter

Model	0 m, -100 m – -500 m		0 m, -100 m		0 m, -200 m		0 m, -300 m		0 m, -400 m		0 m, -500m	
Concordance and SE	0.746	0.016	0.696	0.027	0.678	0.027	0.728	0.028	0.762	0.026	0.772	0.026
Variable	Coef	P-value	Coef	P-value	Coef	P-value	Coef	P-value	Coef	P-value	Coef	P-value
Waterway Distance	-3.68633	1.49e-06 ***	-7.3006909	9.61e-06 ***	-4.25323	2.45e-05 ***	-3.728023	1.68e-05 ***	-3.527178	1.41e-05 ***	-2.773354	0.000171 ***
Density - Sparse							0.891047	0.00147 **	1.057971	0.000171 ***	1.114907	7.68e-05 ***
ESSFdkp	1.25175	0.000430 ***	1.5288932	0.039292 *			2.084428	7.45e-05 ***				
FBP NF	1.80669	1.92e-13 ***	1.7654908	6.41e-06 ***	2.7929	7.52e-15 ***	1.528156	2.95e-06 ***	2.355265	1.54e-12 ***	2.102401	2.89e-10 ***
Shrub - Low			1.2669285	0.000852 ***	0.87616	0.000432 ***	0.777499	0.00362 **				
IMAun	2.23091	4.80e-05 ***	2.3452085	0.035828 *							2.956617	0.014300 *
FBP C2	-0.95389	0.004342 **	-1.1956072	0.028158 *	-1.1994	0.005096 **			-1.569353	0.002281 **	-1.359351	0.001818 **
FBP C3									-0.463112	0.062700 .	-0.507198	0.025861 *
Stand Age							0.004606	0.00158 **	0.003208	0.030215 *	0.003638	0.007495 **
Slope	0.02251	0.005816 **							0.038133	0.000421 ***	0.034629	0.000689 ***
ESSFdku							1.350119	0.00153 **	2.030439	0.000149 ***	1.938938	0.000107 ***
FBP 01AB	0.80745	3.78e-05 ***										
Density - Dense									-0.562721	0.419438	0.855923	0.009076 **
Dense and Age									0.038133	0.007698 **		
TWI					-0.04588	0.018434 *						
Herbaceuous	-2.11241	0.001716 **										
ESSFdk	-1.15738	4.32e-07 ***										
MSdk	-1.53332	0.014986 *										
TPI	0.53898	0.028565 *					0.979181	0.01384 *				
Density - open			-1.0687081	0.002497 **								
FBP – C7							-1.005784	0.02928 *	-1.318574	0.009572 **	-1.644926	0.000708 ***
Crown Closure							0.109363	0.01230 *				

Table 12: Comparison of models for equidistant sample points from the fire perimeter

Model	-40 m, 40 m		100 m, -100 m		200 m, -200 m		300 m, -300 m		400 m, -400 m		500 m, -500 m	
Concordance and SE	0.656	0.022	0.763	0.026	0.834	0.023	0.808	0.024	0.904	0.019	0.887	0.019
Variable	Coef	P-value	Coef	P-value	Coef	P-value	Coef	P-value	Coef	P-value	Coef	P-value
Waterway Distance	-5.0029	0.000700 ***	-3.7731	0.000680 ***	-2.196988	0.01868 *	-3.070837	0.001661 **				
Density - Sparse	-0.5888	0.020171 *	1.23868	0.000211 ***			3.693227	2.25e-08 ***	2.745058	0.000193 ***	1.058688	0.001549 **
ESSFdkp			2.17007	0.001812 **			2.764806	5.95e-06 ***	2.2949	0.003886 **	2.051683	0.004703 **
FBP NF	1.07396	7.04e-06 ***	2.48984	7.76e-09 ***	4.158494	< 2e-16 ***	3.414235	1.22e-15 ***	3.559066	2.87e-10 ***	2.287882	3.34e-05 ***
Shrub - Low			1.71396	0.000128 ***								
Sparse and Low Shrub			-2.2877	0.002461 **								
IMAun			2.7712	0.003573 **							3.526631	0.002687 **
FBP C2	-1.6718	0.000401 ***	-1.014	0.036605 *	2.81449	0.00840 **						
Wetland	2.40499	0.022122 *	1.80437	0.028985 *			3.635134	0.001553 **	6.424009	1.61e-05 ***		
FBP D1			-0.766	0.031558 *	-1.062338	0.02996 *			-2.251935	0.001806 **		
Shrub - Tall												
FBP C3												
FBP Water												
Stand Age					0.003366	0.03902 *	0.00762	0.000272 ***	0.00928	0.000251 ***	0.005942	0.001254 **
Slope	0.0244	0.014784 *			0.014319	0.24794			0.097874	3.76e-06 ***	0.045984	0.000197 ***
ESSFdku									4.216387	2.97e-05 ***	3.596972	5.45e-05 ***
ESSFdku and Grass												
FBP 01AB					0.938285	0.00288 **	1.260063	0.000308 ***				
Denisty - Dense												
Dense and Age												
HLI												
FBP M												
ESSFdku and age												
TWI											0.083593	0.009162 **
Density - open	-1.5827	7.72e-11 ***			-0.770334	0.00585 **						
ESSFdk	-0.7447	0.006590 **					0.515349	0.496472	1.784305	0.067010 .		
ESSFdkw	-1.0261	0.006750 **										
FBP C7					0.88709	0.05719 .						
TPI							1.596493	0.006171 **	1.193191	0.086528 .	0.153264	0.766629
ESSFdk and Slope							-0.064903	0.010122 *	-0.121774	0.000132 ***		

ESSFdk and Wetland				-5.963348	0.001579 **				
Sparse and Age				-0.014253	4.16e-05 ***	-0.011945	0.002021 **		
FBP M						-4.193726	0.004359 **	-2.248527	0.000384 ***
Crown closure						-0.075239	0.279163		
ESSFdku and crown closure						-0.581467	0.000661 ***		
ESSFdk and age								-0.011733	0.005027 **