Historical Fire Regime of the Darkwoods:

Quantifying the Past to Plan for the Future

by

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Abstract

This study quantifies the fire history of the Darkwoods; a 55,000 ha property in the South Selkirk Natural Area of southeastern British Columbia, owned and managed by the Nature Conservancy of Canada. Fire scar and tree cohort chronologies from 45 plots, extending from the years 1406 – 2010, were used to determine the temporal and spatial variability of historic fires in ~4,000 ha of the southeastern-most watershed of the property, and to assess the accuracy of provincial Natural Disturbance Type (NDT) classes for the study area. In light of a mixed-severity fire regime, new and novel methods of historic fire mapping using Inverse Distance Weighting methods in a GIS were also analyzed.

Using logistic regression, the spatial variation of fires at the tree- and plot-levels differed greatest by elevation, but fires at the tree-level also varied by slope steepness and slope aspect. Anthropogenic influences on the occurrence of fire over time were also evident, but only after 1945, when the occurrence of fire dropped significantly likely due to the introduction of modern methods of fire suppression in the 1940s. Results indicate a mixed-severity fire regime for the study area, and the presence of numerous fire scars in mid- and high- elevation plots, in conjunction with mean fire return intervals less than 100 years, provide evidence that conflicts with provincial NDT designations.

Including high-elevation stand ages, determined from increment cores, provided evidence of the absence of fire and helped refine estimates of fire boundaries, particularly in and around areas experiencing mixed- and high-severity fires. Spatial Mean Fire Intervals were longer than those calculated at the tree-, plot- and watershed-levels, reflecting the degree to which a mix of high-severity, stand-replacing fires, with low- and moderate-severity, stand-maintaining fires, can lengthen mean return intervals across a mixed-fire landscape.

Table of Contents

List of Tables

List of Figures

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Chapter 1: Introduction

Forest managers are challenged with ensuring healthy, sustainable ecosystems and landscapes capable of providing a broad range of commodity and amenity values while simultaneously providing critical habitat for endangered plant and animal species (Camp et al. 1996). As such, management decisions are guided by specific management goals, including wood production, park or wilderness management, or wildlife habitat (Agee 1993). With goals of habitat restoration, for example, management decisions focus on "restoring" current conditions or processes to levels that function within a historic range of variability (HRV), the range of which was determined by the historic temporal and spatial distribution of natural ecological processes and structures (Swetnam et al. 1999; Wong and Iverson 2004).

Natural disturbances are examples of ecological processes that operate at different temporal and spatial distributions, and are defined as any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment (White and Pickett 1985). In forest ecosystems, disturbance events, controlled primarily by regional climate and local topography, drive forest structure at various temporal and spatial scales (Turner et al. 1993; Lertzman and Fall 1998; Swetnam and Betancourt 1998; Wong et al. 2003). These disturbances manifest through biotic and abiotic agents such as drought, landslides, windthrow, insect and disease outbreaks, and humans (White and Pickett 1985; Swetnam and Betancourt 1998; Wong et al. 2003a, 2003b). Wildfire, in particular, is one of the most dramatic and most costly disturbance events – monetarily, ecologically, and in human life – that forest ecosystems endure (e.g., Blackwell et al. 2003). The escalation in wildfire activity over the past 30 years has been associated with changes in ecosystem health and stability (Blackwell et al. 2003), the level of which has been linked to climate variability of the past three centuries (Johnson and Larsen 1991; Swetnam and Baisan 1996; Lutz et al. 2009).

To properly assess fire as a disturbance mechanism and guide ecologically-based management, several questions must be asked: How do regional climate and local topographic factors effect fire? Have humans recently affected or altered the natural cycles of fire? How have the spatial and temporal variations of historical fires impacted current forest structures and dynamics? What are the possible implications for management strategies? When managing land for a specific purpose, such as habitat restoration, these questions become increasingly important, but take on a tone of the past; understanding the HRV becomes the underlying focus.

This study addresses these questions by quantifying the effects of wildfire as a disturbance agent in the forests of the Darkwoods, presently the largest single private land purchase for conservation in Canadian history (Nature Conservancy of Canada 2008). In an effort to address current management goals of understanding the role of fire in the landscape of the Darkwoods, this study will address one aspect of the HRV: the historic fire regime (HFR). To accomplish this, I quantify both the historic and modern fire regimes to assess the level of departure from historic trends. I focus on local topography (bottom-up) and anthropogenic impacts as controls on the HFR.

1.1 Fire Regime Research

In studies of fire history, the term *fire regime* is used to describe the nature of fires occurring over an extended period of time for a defined study area (Brown 1995). Fire regimes reflect the fire environment, and influence the type and abundance of fuel, thereby affecting fire behaviour and fire effects through time (Morgan et al. 2001). Since the early 1980s, a range of descriptors for fire regimes have been developed, including frequency, magnitude (severity and intensity), predictability, size, seasonality, and spatial patterns (Heinselman 1981; Pickett and White 1985; Agee 1993; Crutzen and Goldammer 1993; Morgan et al. 2001). When considering fire as a disturbance mechanism, the most widely accepted method of quantifying a fire's impact is by its frequency and level of severity. Fire frequency is simply a measure of the timing between fire events over time, often expressed as a fire return interval, probability of occurrence, or rotation period (White and Pickett 1985; Agee 1993). Fire severity is broadly defined as the degree of ecosystem change induced by fire (Ryan and Noste 1985) and, in forest environments, is measured through the degree of tree mortality (Agee 1993).

The frequency and severity of fire events depend on regional (top-down) and local (bottom-up) environmental factors, as well as anthropogenic impacts that control combustion. Combustion is a rapid oxidation process, the susceptibility of which depends upon the condition of the fuel and the amount of heat and oxygen available (Agee 1993). The interactions of these three factors are referred to as the fire triangle (Agee 1993).

By controlling the condition of the three components of combustion, environmental and anthropogenic factors also affect the variability of fire, either directly or indirectly. This variability results in temporal and spatial heterogeneity in fire, evident across a gradient of scales (Lertzman et al. 1998). Often, this heterogeneity produces variability in fire behaviour, visible as a patchy mosaic of forest stands across the landscape.

1.1.1 Controls on Fire Regimes

1.1.1.1 Top-Down

"Top-down controls" refer to situations where the fire regime is affected by environmental factors at coarse, broad scales, driven primarily by climate and the variations within (Cyr et al. 2007). Climate determines the prevalence of severely wet or dry conditions, often varying within the elevation or latitude.

Studies of fire history relate fire occurrence to climatic oscillations that produce conditions conducive to fire. Observed oscillations include the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) (Swetnam and Batencourt 1998; Heyerdahl et al. 2002; Gray et al. 2004). Severe fire events are triggered by drought conditions that exacerbate the drying of live and dead fuels.

1.1.1.2 Bottom-Up

Environmental factors that vary at fine, local scales, such as elevation, slope angle, slope position, aspect, and physiography (e.g., the shape of the land, affecting factors such as wind and evaporation), are examples of bottom-up controls (Agee 1993). Bottom-up controls are frequently reported as dominant influences of fire regimes in landscapes with very complex topography (see Veblen et al. 2000; Heyerdahl et al. 2001; Schoenaggel et al. 2004; Heyerdahl et al. 2007).

Bottom-up controls are of particular importance in fire history studies because they influence microclimate, thus affecting the amount and condition of fuel indirectly (Heyerdahl et al. 2007). At the regional level, elevation forces an inverse relationship with temperature through environmental lapse rates, affecting both the distribution of species and the length of the fire season (Agee 1993). In general, higher elevations exhibit cooler and more mesic conditions, while lower elevations are warmer and dryer. Slope steepness affects fire directly; steeper slopes cause fire to spread faster by preheating fuels through radiant and convective heating (Agee 1993). The starting position of a fire on a slope affects the behaviour and rate of spread directly; fires starting at the top of a slope are more likely to exhibit backing and flanking behaviour, while those starting at the bottom of a slope are more likely to exhibit a head fire (Agee 1993). Slope aspect influences fire behaviour indirectly by affecting fuel moisture. South aspects exhibit warmer and drier conditions, the result of higher evaporation due to more direct solar insolation. In contrast, north aspects are typically cooler and more mesic (Agee 1993).

1.1.1.3 Anthropogenic Influence

While reflecting past geological and climatological events, the forests on the landscape today also reflect the influence of First Nations, European-American settlers, and present inhabitants (Agee 1993). In forests of the Pacific Northwest, fire has only been relevant for perhaps the past 10,000 years (Agee 1993), once being the dominant ecological process (Jensen and McPherson 2008). However, recent (i.e., within the last 150 years) changes in land-use practices have resulted in immediate and profound effects on forest structures. As such, ecosystems adapted to fire may exhibit shifts in composition and structure as fire is excluded. By extension, this will also affect the future timing (occurrence/frequency), magnitude (intensity/severity) and size (spread/extent) of fire in the area (Agee 1993).

First Nations use of fire has been documented through oral histories and stories dating back for centuries (Barrett and Arno 1982). The specific purposes of their burning practices are not entirely certain, but may have been most important as a subsistence technology (Barrett and Arno 1982). In addition to natural sources of ignition (e.g., lightning), the importance of understanding First Nations use of fire relates to the temporal duration of the practice. Ecosystems suitable for wildlife habitat at one point in time were likely so because of their structural and compositional characteristics. These characteristics evolved over millennia, partially in response to the occurrence and spread of fire (White and Pickett 1985; Taylor 2000), whether ignited naturally or by First Nations. Therefore, any change in the occurrence and spread of fire could alter the characteristics of the ecosystem (Taylor 2000), possibly to a point where conditions are no longer suitable for specific wildlife species.

Since Euro-American settlement in the mid-1800s, changes in land-use practices have produced alterations in the occurrence and spread of fire (Jensen and McPherson 2008). Mining and ranching practices often involved the setting of fires, either to clear land for mining surveys or to develop pasture land, while logging practices directly altered forest structures through clear-cuts (Barrett and Arno 1982). As a result, the occurrence and spread of fire was greatly altered (Veblen et al. 2000). Furthermore, the suppression of smaller, less-intense fires in the defence of homes and towns was common practice (Barrett and Arno 1982). The most significant reduction in fire occurrence and spread, however, has been associated with the advent of modern methods of aerial suppression in the 1940s, including “rapid response” attack (e.g., manual methods via helicopter and parachute) and aerial water tankers (Fulé et al. 1997; Brown et al. 1999; Taylor 2000; Veblen et al. 2000). Improved lightning detection via ground, air and space-based systems has also enabled quick response to potential ignition locations, resulting in the suppression of fires within minutes after they start.

1.1.2 Classifications of Fire Regimes

Fire regimes affect the distribution of species, age-class distribution of stands, characteristics of wildlife habitats, vulnerability of forests to insect epidemics, net primary production and carbon balance (Cyr et al. 2007). Thus, understanding the drivers of fire regimes is important when comparing the past with the present (Arno and Fiedler 2005). Fire regime classifications provide a frame of reference for understanding how trees, other plants, animals, and soil organisms form dynamic communities, each adapted to certain frequencies and intensities of burning (Brown 2000).

1.1.2.1 Low-Severity Fire Regimes

Also termed *understory* (Arno and Feidler 2005) or *stand-maintaining* (Swetnam et al. 1999) fire regimes, low-severity fire regimes are characterized by frequent fire events and a high survival rate of over-story trees (Agee 1993, Sherriff and Veblen 2006). Low-severity fires burn abundant contiguous, fine surface fuels in the understory. These fires typically occur in dry, low-elevation forests comprised primarily of thick-barked tree species (Schoennagel et al. 2004). Thick bark allows for a high degree of fire-tolerance, whereby many trees will survive fire events and form cambial scars, a direct adaptation to fire

(Meidinger and Pojar 1991, Brown and Wu 2005, Swetnam et al. 2011). These characteristics result in the regeneration of forests with sparse, open-canopies with few ladder fuels, conditions ideal for species such as ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*) and western larch (*Larix occidentalis*) (Meidinger and Pojar 1991, Brown and Wu 2005).

Low-severity fire regimes are shaped primarily by bottom-up, local topographic controls, with periodic top-down control (e.g., ENSO) (Agee 1993, Swetnam and Baisan 1996, Grissino-Mayer and Swetnam 2000, Kitzberger et al. 2001). In general, this regime is characterized by short-term temporal variation, as fires return more frequently, and fine-scale spatial variation, as fires burn smaller areas (Agee 1993; Lertzman et al. 1998; Veblen et al. 2000; Heyerdahl et al. 2001; Schoennagel et al. 2004).

Forests of this regime have been strongly affected by anthropogenic fire exclusion (Schoennagel et al. 2004). Since changes in land-use patterns in low-elevations forests began during Euro-American settlement of the west in the 1850s, and with the introduction of modern methods of fire suppression in the 1940s (e.g., smokejumpers and aerial water tankers), fire return intervals have lengthened. In absence of fire, these forests have been allowed to grow denser, creating unnatural accumulations of understory and ladder fuels that are capable of carrying fire into the canopy (Schoennagel et al. 2004). As a result, the severity of recent fires has increased in many of these forests. In these forests, fuel reduction treatments, such as manual and mechanical thinning and prescribed fire, are likely to be effective in mitigating extreme fire behaviour, and in restoring the affected forest type to its historical fire regime (Agee 1993; Swetnam and Baisan 1996; Fulé et al. 1997; Schoennagel et al. 2004).

1.1.2.2 High-Severity Fire Regimes

Also termed *stand-replacement* fire regimes (Arno and Fiedler 2005), high-severity fire regimes are characterized by infrequent fire events, defined by a high-degree of mortality in canopy trees (Agee 1993, Sherriff and Veblen 2006). High-severity fires typically dominate in cool, moist, and dense high-elevation forests with a large proportion of thin-barked tree species, a characteristic that reduces fire-tolerance (Schoennagel et al. 2004). Left undisturbed, forests existing in these conditions will mature through stages of stand development, resulting in dense, multi-layered, closed-canopy forests. These characteristics provide an abundance of ladder fuels, where shade-tolerant species are the best competitors. Given the structure of these forests, fire events are usually very intense, carrying easily through the treetops (crown fires) but also killing trees through very hot surface fires (Schoennagel et al. 2004).

Following a high-severity fire, few or no trees survive so that growing space and sunlight are not limited, providing shade-intolerant species with ideal conditions to out-compete shade-tolerant species. In the western United States and Canada, early successional species with serotinous cones, such as lodgepole pine (*Pinus contorta*), are often the quickest to establish following high-severity fire events (Johnson and Fryer 1989, Johnson et al. 1994, Nyland 1998, Antos and Parish 2002, Axelson et al. 2009). Given a long enough time-period, however, undisturbed lodgepole pine stands are eventually succeeded by stands of longer-lived shade-tolerant species, such as Englemann spruce (*Picea engelmanii*) and, in the higher elevations, subalpine fir (*Abies lasiocarpa*), that are more characteristic of mesic, high-elevation regions (Johnson and Fryer 1989, Jenkins et al. 1998).

High-severity regimes are generally driven by top-down, regional climatic control, directly affecting the moisture content of live fuels and larger dead fuels. This regime experiences infrequent temporal variation and coarse-scale spatial variation, as fires occur less often but burn larger areas (Lertzman et al. 1998; Kipfmueller and Baker 2000; Veblen 2000; Schoennagel et al. 2004; Sibold et al. 2006).

Due to the infrequent nature of high-severity fire events in subalpine forests, the short period of anthropogenic influences has not significantly altered the long fire intervals associated with the high-severity fire regime (Schoennagel et al. 2004; Reinhardt et al. 2008). For purposes of habitat or ecological restoration, the costly methods of manual and mechanical thinning are not appropriate as they are counter to the natural processes of these forests; thinning may negatively affect forest structure and composition, allowing uncharacteristic species to succeed where they otherwise would not (Veblen 2003; Romme et al. 2004; Schoennagel et al. 2004; Reinhardt et al. 2008). Furthermore, many high-elevation forests within a high-severity fire regime are within the historic range of variation, deeming methods of manual and mechanical thinning unnecessary. However, in cases where mitigation is deemed necessary, such as in the wildland-urban interfaces (WUIs) of rural towns and villages, the benefits of reducing risk to infrastructure, homes and human lives can outweigh the high costs of manual and mechanical thinning (Reinhardt et al. 2008).

1.1.2.3 Mixed-Severity Fire Regimes

Mixed-severity regimes are the result of complex combinations of high-severity, stand-replacing fires, and low- and moderate-severity, stand-maintaining fires (Agee 1998, Schoennagel et al. 2004, Sheriff and Veblen 2006). Mixed-severity fires typically occur in mixed-composition forests (e.g. mixed-conifer) at mid-elevations, where topographic variation creates complex moisture gradients (Agee 1998, Schoennagel et al. 2004, Sheriff and Veblen 2006).

Mixed-severity regimes are characterized by both top-down and bottom-up controls. They occur with mixed temporal variation (fires return frequently and infrequently, depending on level of control) and mixed spatial variation (fires burn within a gradient of small to large areas) (Lertzman et al. 1998), and exhibit return intervals that tend to longer than an exclusively low-severity fire regime (Sheriff and Veblen 2006). Variation also occurs within and among individual fire events, as evidenced by variable fire behaviour (Lertzman et al. 1998; Schoennagel et al. 2004). As a result, forests in mixed-severity regimes are structurally diverse with complex dynamics (Perry et al. 2011).

1.2 Fire Regime Research in B.C.

In British Columbia, forests have been classed into one of five natural disturbance types (NDTs) (BC Ministry of Forests 1995; **Table 1.1**), which guides conservation of biodiversity and management of renewable resources. The NDT system aims to describe the frequency and severity of disturbances, primarily fire. In their present arrangement, NDT classes include combinations of frequent and infrequent events at stand-replacing and stand-maintaining severities, reflecting characteristics of low- and high-severity disturbances well. However, intermediate frequencies and severities associated with mixed-severity disturbances are missing entirely.

Table 1.1 Provincial classes for Natural Disturbance Types (NDTs) in British Columbia, Canada.

Class	Definition	Mean Return Interval
NDT1	Ecosystems with rare stand-initiating events	~250-350 yrs
NDT2	Ecosystems with infrequent stand-initiating events	~200 yrs
NDT3	Ecosystem with frequent stand-initiating events	~100-150 yrs
NDT4	Ecosystem with frequent stand-maintaining events	~4-50 yrs
NDT5	Alpine Tundra and Subalpine Parkland ecosystems	No Data

Recent research in mid-elevation montane forests in British Columbia classified as NDT3 has observed much higher frequencies in historic fire occurrence than is designated by the present NDT classification system (Cochrane 2007, Da Silva 2009, Nesbitt 2010). Thus, forest managers have and may continue to develop strategies preventing the occurrence of low- to moderate-severity disturbances in these forests, reducing their ecological resilience and biodiversity (Cochrane 2007). This is a significant knowledge gap in understanding the role of fire in montane forests of British Columbia (Wong et al. 2003). Due to the intimate link between fire regimes and the variables driving them, it also implies a lack of understanding of the bottom-up and anthropogenic factors controlling fire regimes in montane forests.

1.3 Research Objectives

In this study I will determine the historic range of variability (HRV) of fire in forests of the Darkwoods property to address the knowledge gaps highlighted above, and to assist resource officials in understanding the role of fire in the landscape. In terms of fire as a disturbance mechanism, I will quantify the bottom-up and anthropogenic controls involved. This will allow for a comparison to current conditions in order to assess the level of departure from historic "reference" conditions. I hypothesize that low- and moderate-severity fires played a larger role as a disturbance mechanism than is currently described by the natural disturbance type (NDT) classification system and that topography and changes in human land use are intimately linked in driving these regimes. My study aims to answer the following four questions by testing their associated hypotheses (stated as predictions):

Q1: Does fire occurrence differ by slope aspect?

Fire occurrence varies by aspect, with fewer fires occurring in the cooler, more mesic northeast aspects and more frequent occurrence of fires in the warmer, drier southwest aspects.

Q2: Does fire occurrence differ by elevation according to current NDT classifications?

Fire occurrence varies by elevation, with fires occurring infrequently in the cooler, more mesic high elevations, and more frequent fires in the warmer, drier low elevations. As well, the mid-elevations reflect the overlap between high- and low-elevations and are characterised by a complex mix of both frequent and infrequent occurrences of fire.

Q3: Does fire occurrence differ between the historic fire regime (Pre Euro-American Settlement period) and the periods of Euro-American Settlement and/or Modern Fire Suppression?

Fire occurrence varies by periods of anthropogenic land-use:

i.	Pre Euro-American Settlement	prior to 1860
ii.	Euro-American Settlement	1860 - 1944
iii.	Modern Fire Suppression	1945 - 2010

Q4: Does the inclusion of ring-width series from cored trees, in plots where no fire scars are present, affect reconstructions of historical fires in mixed-severity fire regimes?

Including ages of fire-intolerant tree species in mesic, mid- to high-elevation stands as proxy evidence for the absence of fire will reduce estimated fire boundaries in adjacent stands that include fire scars.

To address the first three research questions, I use traditional dendrochronological methods to determine the year of fire occurrence (Chapter 2). These measures provide for the reconstruction of the temporal and spatial variation in historic fires, and allows for assessment of human impacts on the fire regime during the 20th century. Mean and median fire return interval statistics are used to quantify the timing of fire events across the watershed, and statistical modeling, logistic regression is used to determine the bottom-up controls and anthropogenic influences on the occurrence of fire. The results are compared with the provincial NDT classes in order to assess their accuracy and applicability in the forests of the Darkwoods.

To address the last research question, I use recent and novel methods of Geographic Information Science (GIS) analysis to reconstruct the spatial and temporal variation in historic fires (Chapter 3). Inverse Distance Weighting (IDW) methods introduced by Hessl et al. (2007) and Kernan and Hessl (2010) are used to recreate historical fire boundaries and model the Spatial Mean Fire Interval (SMFI) across the study area. As a novel approach, I include tree ring-width series and ages from fire-intolerant species in mid- to high-elevation plots, where no fire scars are present, as proxy evidence for the absence of fire. Sensitivity analysis is used to compare these results with those generated by conventional methods.

I conclude by summarizing my research findings, and provide suggestions for management strategies in mixed-severity fire regimes (Chapter 4). I also discuss the next steps required to fully characterize the fire regime of the Darkwoods.

Chapter 2: Temporal and Spatial Variation of the Historical Fire Regime

2.1 Introduction

Sustainable forest management aims to conserve biodiversity and maintain ecosystem function while maintaining renewable resources. To achieve this goal requires knowledge of the spatial and temporal attributes of natural disturbance regimes and disturbance impacts on forest composition and structure (Christensen et al. 1996, Landres et al. 1999). In collaboration with The Nature Conservancy of Canada (NCC), I investigate the fire regimes of the mixed-conifer, mountain forests of the NCC's "Darkwoods" property in the South Selkirk Natural Area. I reconstruct the spatial and temporal variation in historic fires and assess human impacts on the historic and contemporary fire regimes. The outcomes of this research have both fundamental and applied value. Presently, mixed-severity fire regimes are poorly understood in British Columbia, reflected by incorrect applications of provincial Natural Disturbance Type (NDT) classifications. Improved knowledge of the mixed-severity fire regime will better inform provincial policies, and will provide NCC land managers with information that is more ecologically meaningful and applicable to their goals of restoring and conserving forest structures and processes for wildlife habitat.

2.1.1 Fire Regime Research

A fire regime is the spatial and temporal variation in fires that burn in a defined landscape over time (Agee 1993). Research in coniferous forests in the western United States and Canada during the past decade has illustrated the tremendous variability in fire regimes in mountain ecosystems.

Spatial heterogeneity, defined as complex patterns of fire over space, is caused by spatial variability in local conditions that influence fire initiation or propagation (Lertzman et al. 1998). At local scales, environmental factors such as elevation, slope aspect, slope steepness and micro-site fluctuation in topography are described as "bottom-up controls" of fire (Agee 1993). Bottom-up controls are frequently reported in landscapes with complex topography (Veblen et al. 2000, Heyerdahl et al. 2001, Schoenaggel et al. 2004, Heyerdahl et al. 2007). They are of particular importance in fire history studies because they influence microclimate, affecting the amount and condition of fuel indirectly (Agee 1991, Heyerdahl et al. 2007). At the regional level, elevation is inversely related to temperature, affecting species distributions, the length of the fire season, fire frequency and severity (Agee 1993). Slope aspect interacts with elevation and influences fire behaviour indirectly by affecting fuel moisture. South aspects exhibit warmer and drier conditions, the result of higher evaporation due to more direct solar insolation. In contrast, north aspects are cooler and more mesic (Agee 1993).

As a result of these topographic influences, several trends in fire regimes have emerged. Low-frequency but high-severity fires generally dominate in cool, mesic subalpine forests where Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) grow at relatively high densities and form closed canopies. High-frequency but low-severity fires dominate in warmer, drier, and lower-elevation pine forests, where species such as Ponderosa Pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) grow in sparser, more open forests (Schoennagel et al. 2004). Mixed-severity regimes are observed in low- to mid-elevations in mixed conifer forests, being driven primarily by complex variations in slope aspect, microtopography, microclimate and forest structure (Agee 1993, 1998; Schoennagel et al. 2004).

Human land-use also influences fire occurrence and can alter historic fire regimes. For over 10,000 years, First Nation's use of fire has been an integral part of the landscape, although the timing and specific purposes of fire are not well understood (Cochrane 2007). Euro-American practices of mining and ranching often involved setting fires to clear land for mineral surveys or pasture land development. Since the late-1800s, industrial logging, including clear cutting, has directly altered forest structure (Barrett and Arno 1982). As a result, the occurrence and spread of fire has been greatly altered (Veblen et al. 2000). Furthermore, wildfires have been actively suppressed throughout much of the 20th century. The advent of modern methods of fire suppression in the early 1900s has significantly reduced fire occurrence and spread in recent decades in much of western North America (Fulé et al. 1997; Brown et al. 1999; Taylor 2000; Veblen et al. 2000).

The impacts of human land use have also been found to vary with elevation. At low elevations where low-severity fire has been reduced or excluded for one to several fire intervals, increased fuel abundance has increased the risk of large, severe fires, particularly in years of extreme drought (Fulé et al. 1997, Swetnam et al. 1999). Generally, high-elevation subalpine forests are least affected by land use change because they are difficult to access and the period of fire exclusion is short relative to historic fire intervals (Schonnagel et al. 2004, Sibold et al. 2006). In mid-elevation forests, impacts are variable, depending on human access and use of adjacent low-elevation forests.

2.1.2 Fire Regime Research in British Columbia

In British Columbia, forests have been classed into one of five natural disturbance types (NDTs) (BC Ministry of Forests 1995; *see* ***Table 2.1***), which guides conservation of biodiversity and management of renewable resources. The NDT system aims to describe the frequency and severity of disturbances, primarily fire. In their present arrangement, NDT classes include combinations of frequent and infrequent events at stand-replacing and stand-maintaining severities, reflecting characteristics of low- and high-severity disturbances well. However, intermediate frequencies and severities associated with mixed-severity disturbances are missing entirely.

Table 2.1 Provincial classes for Natural Disturbance Types (NDTs) in British Columbia.

Class	Definition	Mean Return Interval
NDT1	Ecosystems with rare stand-initiating events	~250-350 yrs
NDT2	Ecosystems with infrequent stand-initiating events	~200 yrs
NDT3	Ecosystem with frequent stand-initiating events	~100-150 yrs
NDT4	Ecosystem with frequent stand-maintaining events	~4-50 yrs
NDT5	Alpine Tundra and Subalpine Parkland ecosystems	No Data

Recent research in mid-elevation montane forests in BC classified as NDT2 and NDT3 has observed much higher frequencies in historic fire occurrence than is designated by the present NDT classification system, with regimes more characteristic of mixed-severities (Cochrane 2007; Da Silva 2009; Nesbitt 2010; Daniels et al. 2011). Thus, forest managers have and may continue to develop strategies preventing the occurrence of low- to moderate-severity disturbances in these forests, reducing their ecological resilience and biodiversity (Cochrane 2007). This is a significant knowledge gap in understanding the role of fire in montane forests of BC (Wong et al. 2003; Daniels et al. 2011). Due to the intimate link between fire regimes and the variables driving them, this also implies a lack of understanding of the bottom-up and human-induced factors controlling fire regimes.

2.1.3 Objective

In this paper, I use tree-rings to reconstruct the historic fire regime of the southeastern-most portion of the Nature Conservancy of Canada's "Darkwoods" property. I explore the bottom-up and human-induced controls of variation in fire, both temporally and spatially, to compare with provincial NDT classifications for this area. To accomplish this, I use mean and Weibull median fire return intervals to quantify the historic fire regime. I implement logistic regression to explore (1) the spatial variation of the historic fire regime by assessing the influences of elevation, slope aspect and slope steepness as bottom-up controls, and (2) the spatio-temporal variation of the historic fire regime due the effects of human land-use patterns between different periods of occupation. I also compare Weibull median return intervals with fire-free intervals among study-sites to assess the degree of departure of the modern fire regime from the historic fire regime. I conclude by discussing the results of this study in light of the NDT classifications designated by the province.

2.2 Methods

2.2.1 Study Area

Owned and managed by the Nature Conservancy of Canada since 2008, the Darkwoods is 55,000 ha of uniquely diverse mixed-conifer forest, located on the southwestern shore of Kootenay Lake, on the leeward side of the Selkirk Range in southeastern British Columbia (**Figure 2.1**). The study site, a 4,000 ha portion of the southeastern-most watershed of the Darkwoods, ranges from 530 to 2,300 m in elevation, experiences mean annual temperature ranges of 8.2 ± 0.7°C (seasonal temperature ranges of -2.7°C in winter and 19.3°C in summer), and receives mean annual precipitation of 631 mm per year (486.3 mm as rain, 144.8 cm as snow; Environment Canada 2010, Creston 49° 6.000' N, 116° 31.200' W, 597.4 m.a.s.l.). The area is composed of a range of soils but is predominantly Humo-Ferric Podzols and Dystic Brunisols, including a small portion of Gleysols along the southeastern-most boundary of the property (BC Ministry of Environment 2009). Biogeoclimatic zones in the study area include Interior Cedar-Hemlock (ICH) in the lower and mid-elevations, and Engelmann Spruce-Subalpine Fir (ESSF) in the high-elevations, with variants including the Very Dry Warm Interior Cedar-Hemlock (ICHxw), the West Kootenay Dry Warm Interior Cedar-Hemlock (ICHdw1), the Ymir Moist Warm Interior Cedar-Hemlock (ICHmw4), and the Dry Mild Engelmann Spruce-Subalpine Fir (ESSFdm) (**Figure 2.2, Table 2.2**; table includes all zones, subzones and variants for the Darkwoods property). Provincial natural disturbance type (NDT) classifications designated within the study area include NDT 2, NDT 3, and NDT 4 (**Figure 2.3, Table 2.2**; table includes all NDT classifications for the Darkwoods property)

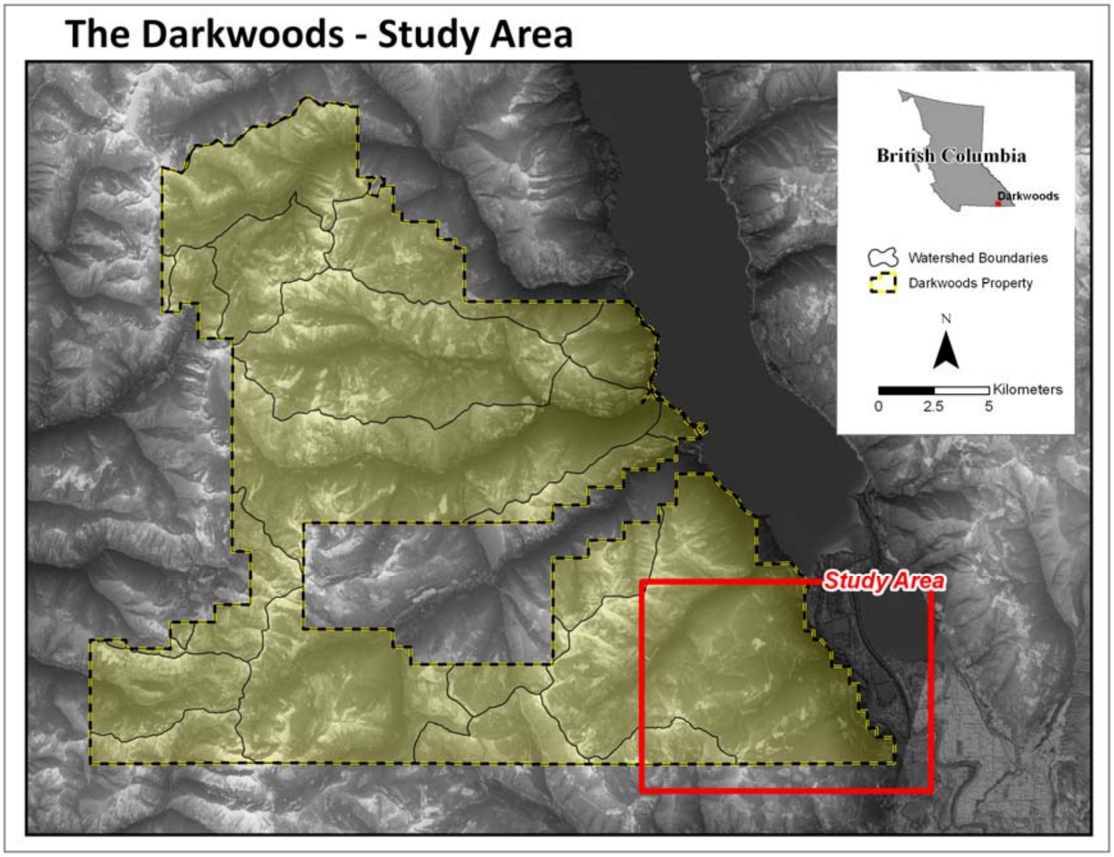

Figure 2.1 The study area and Natural Disturbance Type (NDT) strata as they are currently designated for the "Darkwoods" property.

Forest structure and composition reflects a varying mix of conifers from valley bottom to ridgetop. The lower elevations are dominated by open stands of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) in the warmer and more complex terrain (e.g., rock outcrops), and by dense stands of western redcedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) in the cooler, more mesic areas (e.g., along drainages). Mid-elevations are co-dominated by less dense stands of western larch (*Larix occidentalis*) and Douglas-fir in the warmer aspects, and dense stands of western redcedar and western hemlock in the cooler aspects. The highest elevations are co-dominated by very

Table 2.2 Biogeoclimatic Ecosystem Classification (BEC) Zones and Natural Disturbance Types (NDTs) for the Darkwoods property (Adapted from Meidinger and Pojar 1991, Braumandl and Curran 1992, Braumandl and Dykstra 2005).

Zone Characteristics				*Subzone/Variant/NDT*		
Zone	*Elevation*	*Temperature*	*Precipitation*	*Subzone*	*Subzone/Variant Name*	*NDT*
Interior Cedar - Hemlock (ICH)	400 - 1,500 m	Mean annual range: 2 - 8.7°C; Monthly range: < 0°C for 2-5 mos., above 10°C for 3-5 mos.	Mean annual: 500 - 1,200 mm (25 - 50% as snow)	dw1	West Kootenay Dry Warm	3
				mw4	Ymir Moist Warm	2
				xw	Very Dry Warm	4
Engelmann Spruce - Subalpine Fir (ESSF)	1,500 - 2,300 m	Mean annual range: -2 - 2°C; Monthly range: < 0°C for 5-7 mos., above 10°C for 0-2 mos.	Mean annual: 400 - 500 mm in drier areas, up to 2,200 mm in wetter areas (50-70% as snow)	dm	Dry Mild	3
				dmw	Dry Mild Warm	3
				wc5	Salmo Wet Cold	2
				wc6	Ymir Wet Cold	2
				wcp	Wet Cold Parkland	5
				wcw	Wet Cold Woodland	1
				wm	Wet Mild	1
				wmw	Wet Mild Woodland	1

dense stands of Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), with isolated stands of western larch. Lodgepole pine (*Pinus contorta*) is subdominant across the mid- and high-elevations, and whitebark pine (*Pinus albicaulis*) is scattered throughout the highest elevations.

Darkwoods is located in the traditional territory of the Ktunaxa Nation. The Ktunaxa people have occupied the lands adjacent to the Kootenay and Columbia Rivers and the Arrow Lakes of British Columbia for approximately 4,000 - 10,000 years (Ktunaxa Nation 2005). Fire was an integral part of Ktunaxa use of the landscape, as documented through verbal history (Cochrane 2007).

Beginning in the 1830s, homesteads appeared throughout the Columbia Basin, an area quite isolated until this time (Ktunaxa Nation 2005). In the 1850s, the first Euro-American settlers arrived on the Tye Lot portion of the Darkwoods property (Nature

Conservancy of Canada 2008). Henceforth, land-use practices changed from those established by the Ktunaxa people, of which vegetation and forest structures mirrored and were well-adapted to for at least the last 4,000 years, to those focused on maximizing opportunities for mining, logging and ranching purposes.

Organized methods of fire suppression were introduced in British Columbia with the establishment of the Wildfire Management Branch in 1912 (BC Ministry of Forests and Range 2011). Throughout the early 1900s and into the 1940s, modern methods of fire suppression evolved through the advent of mechanized fire engines, smoke jumpers and aerial water tankers, greatly altering forest structures in BC through a diminished occurrence of less-severe fires (Cochrane 2007, Da Silva 2009, Nesbitt 2010).

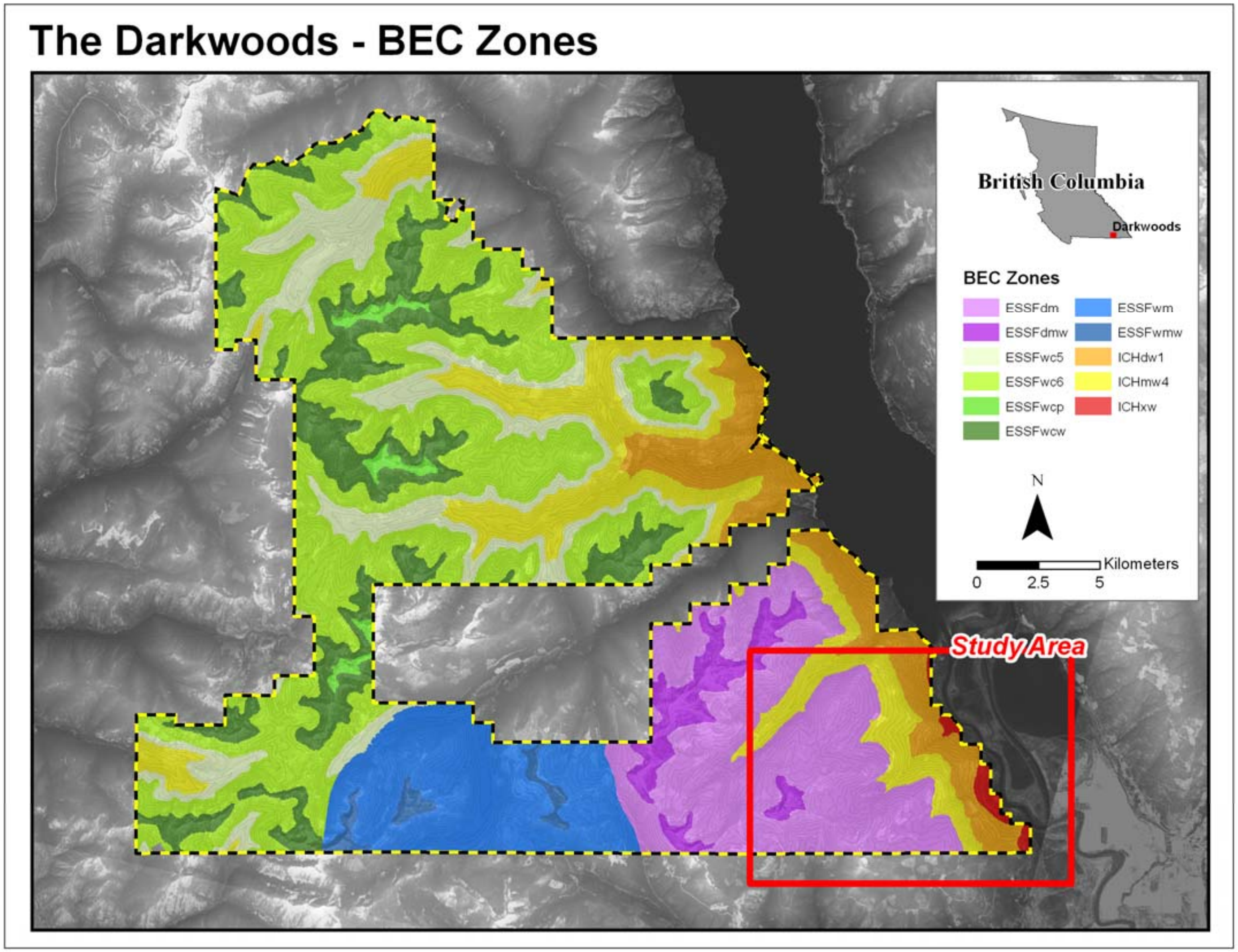

Figure 2.2 B.C. provincial BEC Zones for the Darkwoods property.

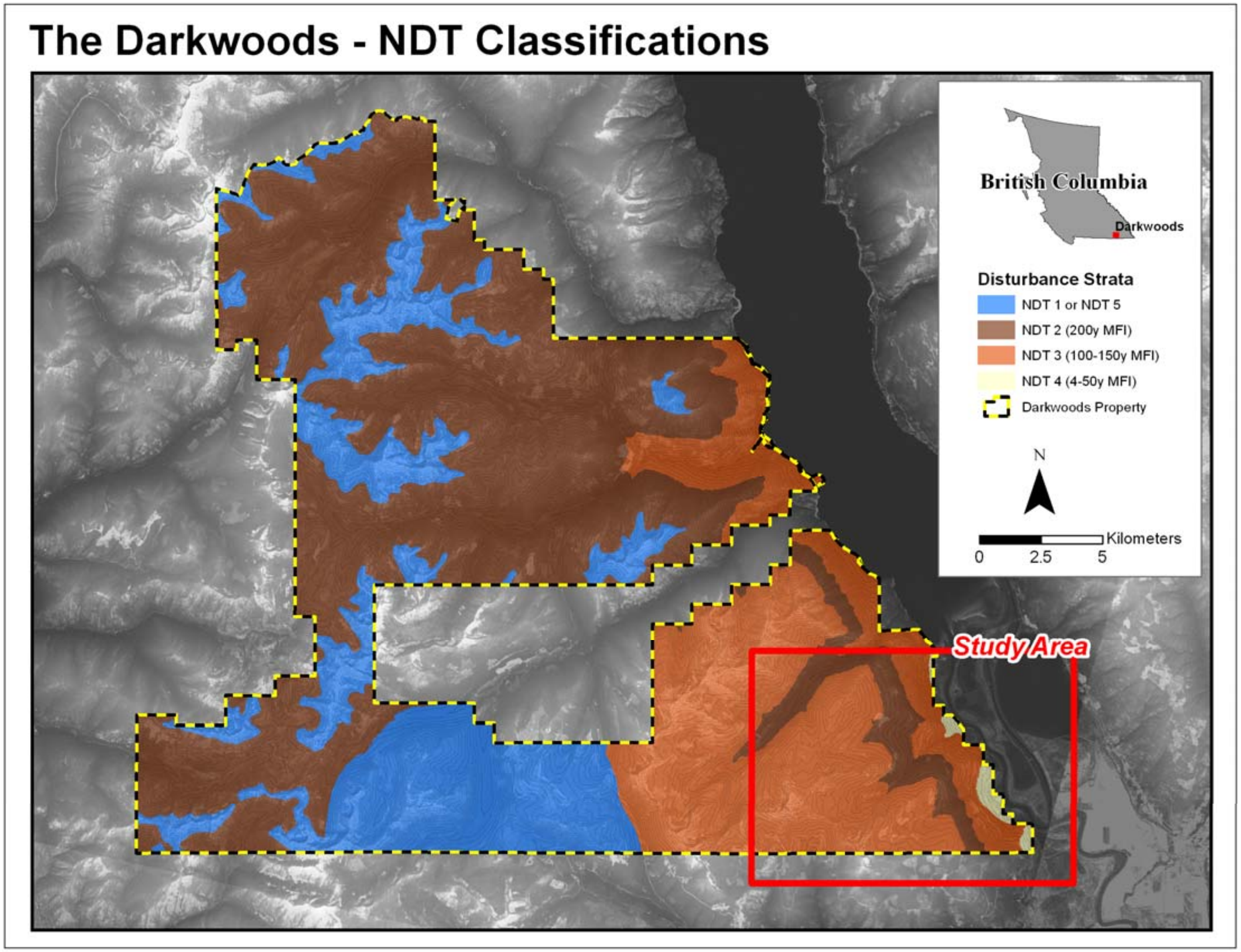

Figure 2.3 B.C. provincial NDT Classifications for the Darkwoods property.

2.2.2 Research Methods and Analysis

2.2.2.1 Systematic Survey

I conducted an intensive, systematic survey of the southeastern-most watershed to determine the occurrence of fire-scarred trees and develop an optimal research and sampling design. Each day, prior to field departure, specific stands were identified in a GIS for survey potential. Selection criteria included species composition, stand age, topography and location. In conjunction with thick-barked, fire-adapted species such as western larch, Douglas-fir and ponderosa pine, stands older than 150 years, in complex terrain, within 500 metres of roads, and either not logged or logged within 10 years were ideal candidates. Stands identified by Darkwoods officials as containing veteran cohorts of these fire-adapted species received priority. Due to the high degree of logging in this portion of the property, stands clear-cut within 10 years were preferentially surveyed for their ease of access, the wealth of information available by viewing stump tops, and to minimize our impact on the forest and surrounding environment once sampling commenced.

Surveys were completed along pre-determined routes, starting and stopping at locations within 500 m of accessible roads, with the goal of reaching the centre of as many stands as possible. Throughout each route, fire-scarred trees were identified and the species, condition (live, snag, stump or log) and number of scars on each specimen were documented. Additionally, the geographic location was recorded with a Trimble GPS and all scarred-trees were photographed.

This initial survey of the southeastern-most watershed of the Darkwoods property revealed a rich potential for fire history. Within 143 stands that encompassed roughly 2,500 ha, I documented 1002 trees as potential fire-scar samples, 620 of which were western larch, Douglas-fir or ponderosa pine. These thick-barked species commonly record fire scars and have been used to reconstruct the fire history of many forests in western North America. Of these 620 thick-barked specimens, 276 were verified to have multiple (at least 2) fire-scar lobes, indicating multiple fires at the site (**Figure 2.4**).

2.2.2.2 Systematic Sampling Design

Due to the wealth of potential fire history sample trees and the complex topographic nature of the southeastern-most watershed, I established 40 plots in a 1 km x 1 km systematic grid, measuring 8 x 11 km (**Figure 2.5**). The southeast corner of the grid was randomly located. This grid was designed to capture variation at the watershed level, allowing for comparison with fire frequencies and severities predicted by the NDT classes.

To be consistent with other fire history studies in the Kootenay region (Cochrane 2007, DaSilva 2009, Nesbitt 2010), I sampled from 1-ha fixed-area plots. One plot was located within 500m of each intersection point of the systematic sampling grid (**Figure 2.5**). To determine suitable plot locations for reconstructing fire history, the GPS locations, field notes and photographs of each fire-scarred candidate were scrutinized. Various locations and configurations of 1 ha plots were explored in GIS to ensure they encompassed at least two suitable specimens. Suitable candidates showed minimal degradation due to rot, were not recognizable as danger or wildlife trees, and were in close enough proximity to include up to seven fire-scar candidates in a 1 ha plot. Plot configurations for fire scar samples were either circular (n = 26, radius = 56.4 m) or rectangular (n = 3; dimensions of 250x40m, 200x50m and 150x66.7m), with rectangular dimensions determined by the proximity of sample candidates.

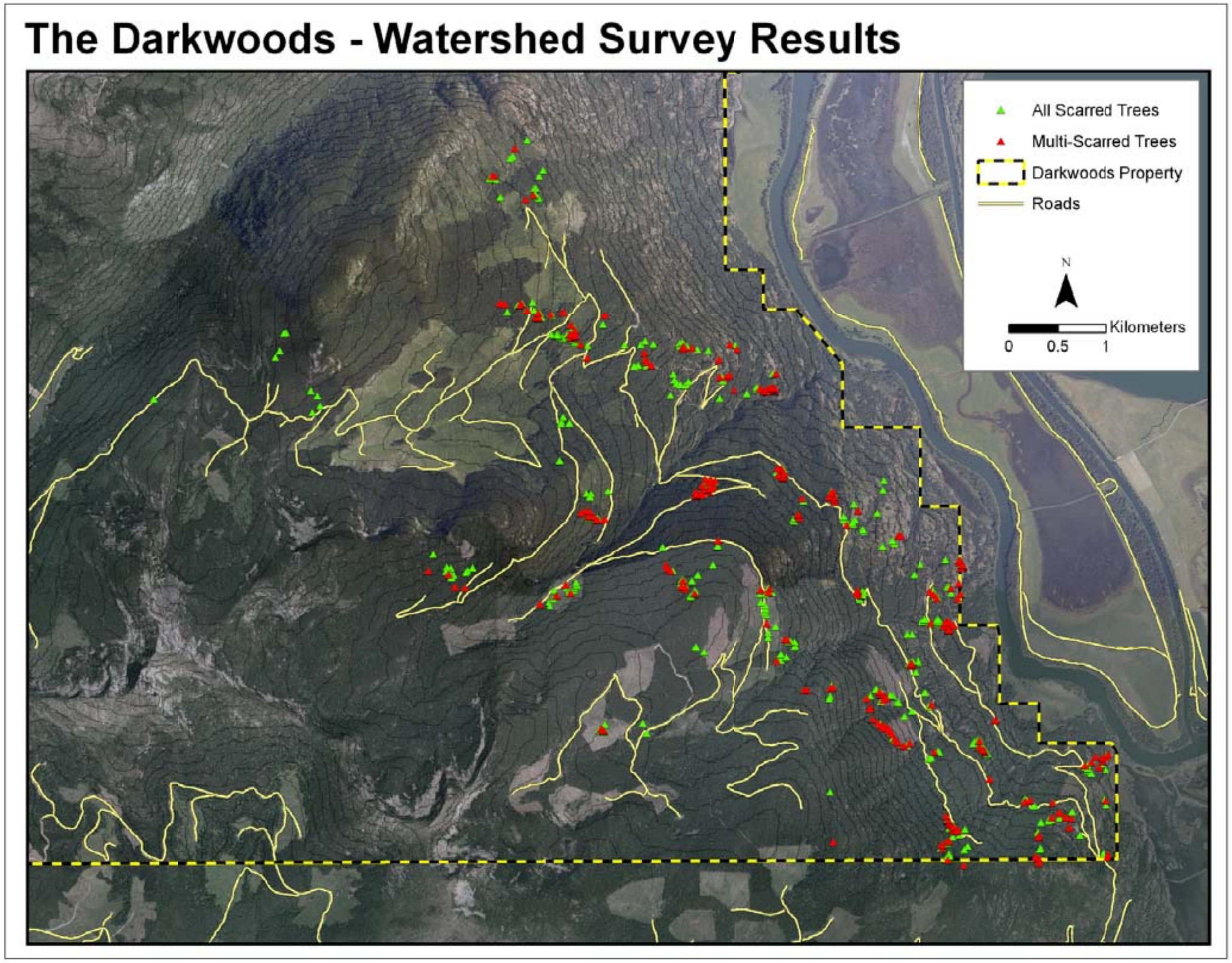

Figure 2.4 Survey results for fire-scarred trees in the southeastern-most watershed of the Darkwoods. Trees with one fire scar are in green, trees with multiple fire scars are in red.

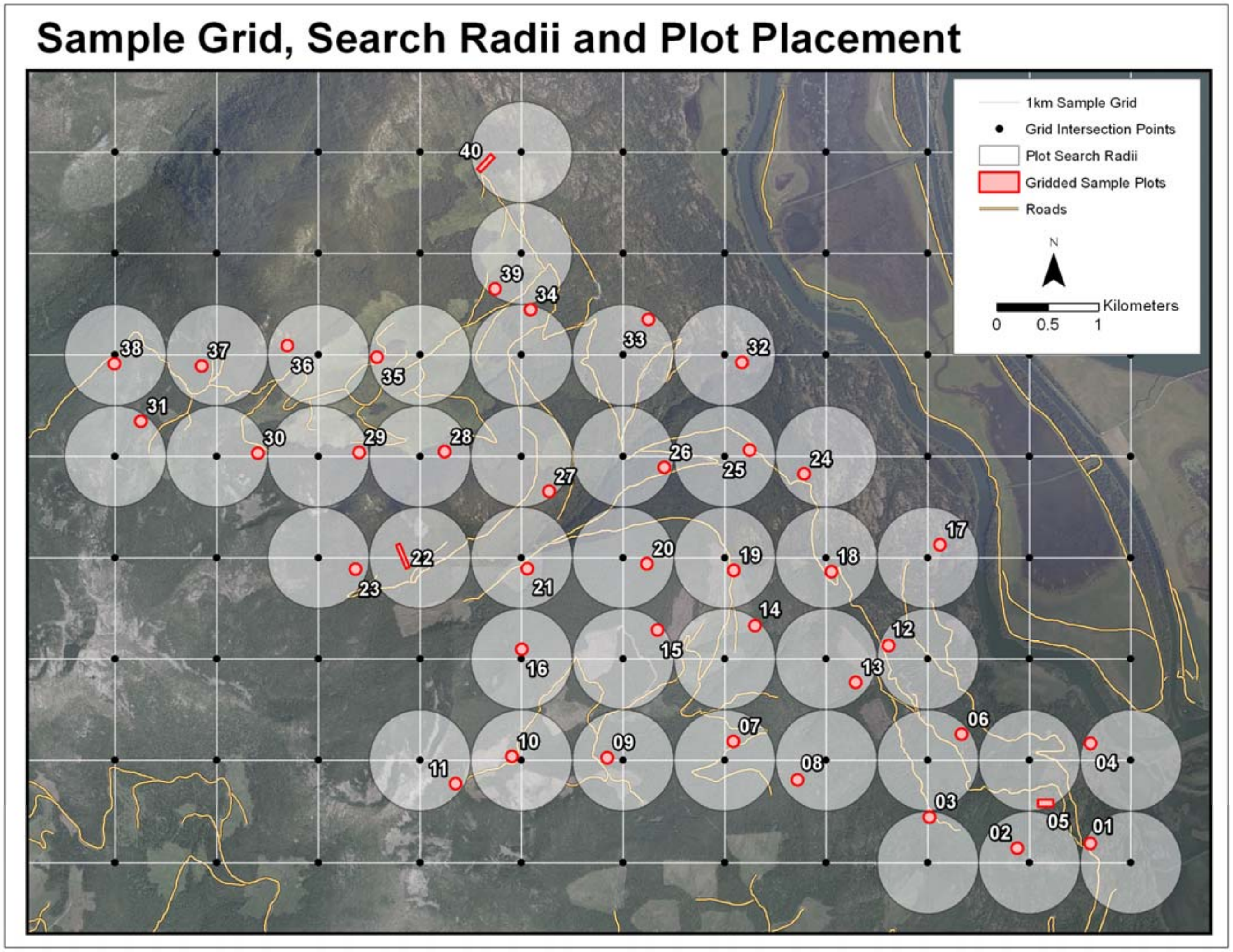

Figure 2.5 Sample grid, search radii, and plots located within 500 m of roads.

No fire scar evidence was apparent in the forests surrounding 15 points in the sampling grid. At these points, I established plots to core canopy trees. The location of these 1-ha circular plots were also selected using a GIS. Stands suitable as coring plots were older than 150 years in order to reduce anthropogenic influence, had no evidence of logging activity, could fit an entire 1 ha circular plot without overlapping adjacent stands, and had to be as close to a road as possible.

2.2.2.3 Sample Extraction

Sampling was a two-step process, involving plot creation and sample extraction. Using a GPS, I located the plot centre for circular plots or a plot corner for rectangular plots. Once located, the position was staked with a 1m-long pvc pipe and plot characteristics were documented. At the plot stake, I photographed the stand in each of the cardinal directions in order to document stand attributes. Using a GPS, the plot UTM location, GPS accuracy, PDOP (a measure of signal quality) and elevation were recorded. As well, I measured slope steepness, slope aspect, and slope configuration (simple or complex).

Fire-scar candidates, previously identified, were re-located and re-evaluated to confirm they were suitable for sampling. In the case of unsuitable samples, the 1 ha plot was surveyed extensively for alternative samples. In plots where many fire-scarred candidates were present, up to seven trees with the most scar lobes that appeared to provide the longest and most robust fire history were selected. Suitable samples were identified with flagging or forestry paint, and their distance and bearing from the plot stake were recorded using a laser rangefinder and compass, respectively. Diameters were recorded at breast height, when possible, or at sample height. Furthermore, supplemental and indirect evidence of fire was documented, including the presence of charcoal in the surrounding soil, the presence of charcoal on the tree itself, and the morphology and position of the scar.

To reconstruct the history of low- and moderate-severity fires within each plot, I used a chainsaw to remove an average of 5 (range: 1-7) fire-scarred samples from trees with the greatest number of visible, well-preserved scars. Stumps and logs were preferentially sampled to minimize impact on the surrounding environment. To reduce impacts on live trees and snags, I removed partial cross-sections whenever safe to do so. All live trees and snags were sampled according to WorkSafe BC protocols (Cochrane and Daniels 2008), including wildlife/danger tree assessments, special documentation of partially cross-sectioned trees, and the falling of trees with dbh > 20 cm by a certified professional faller.

Tree core samples were extracted with increment borers from 10 canopy-dominant trees closest to plot centre. Trees were cored within 30 cm of ground level to increase accuracy in determining tree establishment date. To be efficient with sampling time, I made up to 5 attempts per tree to intercept the pith. When unsuccessful, I chose the sample closest to pith and applied a geometric correction to estimate the number of missed rings and year of tree establishment. All cored trees were measured for distance and bearing from plot centre using a laser rangefinder and compass, respectively, marked with flagging and a unique aluminum ID tag, and all diameters were recorded at breast height. Furthermore, each tree was photographed, documented for species and condition (alive or dead), and locations were recorded with GPS. The presence of charcoal in the surrounding soil was also documented as supplemental evidence for the presence of fire.

2.2.2.4 Sample Preparation

All tree cross-sections and increment cores were processed and analyzed according to standard dendrochronological methods (Stokes and Smiley 1968, 1996). Samples were sanded until the cell structure was visible with a binocular microscope and calendar years were assigned to tree rings using a combination of visual cross-dating of ring widths and cross-correlation of measured ring-width series (Holmes 1983, Grissino-Mayer 2001a). I could not date samples from four of the cross-sections and six of the increment cores, and so excluded them from further analysis.

2.2.3 Assessment of the Historical Fire Regime

2.2.3.1 Fire History

Fire intervals were calculated at the tree, plot, and watershed levels to allow comparison among spatial scales and with other fire history studies. Mean point fire intervals (MPFI) were calculated by averaging the time between fire events on individual fire-scarred trees, the smallest unit of measure in fire history studies. Trees are not perfect recorders of fire, as fire scars may fail to form in less-severe fire events, or may be erased from the record by subsequent fires, mechanical damage, or rot (Van Pelt and Swetnam 1990, Parsons *et al.* 2007, Swetnam *et al.* 2011). Therefore, MPFI is subject to false negatives, potentially overestimating fire return intervals (Kilgore and Taylor 1979, Fall 1998, Baker and Ehle 2001). This issue is overcome by assembling composite fire records (CFR), which are amalgamations of fire scar data for individual trees that summarize the fire history for a given area (Dieterich 1980). A CFR can offset the case of false negatives by including trees that may have scarred when others did not, therefore capturing a more complete representation of an area's fire history (Swetnam *et al.* 2011). For these reasons, CFR are more meaningful for management decisions than individual tree data.

Composited, plot-level fire intervals (CPFI) were calculated for the period after which 28% (n=7) of the fire history plots had recorded fire on at least one tree (1690 – 2010). Minimum, maximum, mean and Weibull median probability interval (WMPI) were calculated from fire interval distributions for all fires using the computer program FHAES, an updated version of the program FHX2 (Grissino-Mayer 2001b). The number of years since the last fire (TSLF) were determined for each site, and recorded as a fire-free interval (FFI). Plots were deemed to be outside the historic range of variability whenever the FFI exceeded the WMPI. Composited, watershed-level fire intervals (CWFI) were also calculated.

2.2.3.2 Logistic Regression: Spatio-Temporal Variation

The influence of topography and human land-use patterns on fire occurrence was assessed using logistic regression to model the log odds ratio, called a logit (SAS Proc GENMOD: link=Logit; SAS Institute 2010). The fire records for individual trees were used to estimate the probability of fire across the watershed using the following logistic regression model (SAS 9.2):

$$P = \frac{e^{M_F}}{1 - e^{M_F}} \tag{1}$$

where P is the probability that fire will occur and M_F is the model of the fire log odds ratio. In this application, the model of the fire log odds ratio (M_F) included multiple independent variables (x_i):

$$M_F = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 ... \tag{2}$$

where, α and β_i were calculated regression coefficients. Topographic influence on the spatial variation of fire occurrence was tested using the continuous independent variables of elevation, measured in metres above sea level (m.a.s.l.), slope aspect and slope steepness, both measured in degrees. Slope aspect, ranging from 1° to 360°, was converted to a linear scale, ranging from 0 (corresponding to 45°) to 180 (corresponding to 225°) (after Parker 1982), to reflect differences between cooler and warmer aspects.

The independent class variable, Period, was also included to assess the impacts of anthropogenic land-use patterns on the fire regime. Period IV, Modern Fire Suppression: 1945-2010, captures potential effects on the occurrence of fire as a result of modern methods of fire suppression during and after World War II (Agee 1993). The remaining portion of the time period, 1690 – 1944, was divided into three equal 84 year segments, each capturing changes in land-use patterns and their potential effects on fire occurrence. Period III, Euro-American Settlement: 1860-1944, captures effects on the occurrence of fire after Euro-American settlement on the Darkwoods property and in the adjacent Creston Valley, and Periods I (Pre-Euro-American Settlement I: 1690-1774) and II (Pre-Euro-American Settlement II: 1775-1859) capture effects of land-use patterns prior to the arrival of Euro-American settlers. While I expect similar land-use patterns between these first two periods to yield only minute differences in the occurrence of fire, Period I may suffer from a lack of sample depth, potentially underestimating the occurrence of fire among sample sets. Therefore, Period II was used as a reference to determine significant levels of departure in fire occurrence after Euro-American settlement on the property in 1854. Interactions between periods of land-use and the topographic continuous variables were also explored to assess human-induced variation in the occurrence of fire across space. In these models, continuous and class variables alter the model's intercept, while interactions of class variables with continuous variables alter the slopes of the affected continuous variable.

Due to the annual relationship between tree-rings, I included a General Estimating Equation (GEE) to account for first-order temporal autocorrelation (i.e., type = AR(1)) as a repeated measures component of the analysis of covariance structure, and accounted for correlation of data between samples within plots (i.e., subject = sample(plot)). All levels of significance were based on an alpha level of 0.05 (α=0.05) using asymptotic z-tests and p-values produced from pseudo-likelihood-ratio and score tests.

2.2.3.3 Provincial NDT Classes

For each plot, I determined the BEC unit and NDT class from the forest cover database. Preliminary analyses revealed an illogical representation of fire history at the landscape level (Figure 3). From low to high elevation in the study area, the four most abundant BEC units are ICHxw, ICHd1, ICHmw, and ESSFdm (**Figure 2.2**). The corresponding NDT classes are NDT4, NDT3, NDT2, and NDT3 (**Figure 2.3**). This pattern implies that historic fire frequency was lower in the mid-elevations than at higher elevations, which is inconsistent with well-documented fire behaviour and fire regime trends (Agee 1993). Instead, it is likely an artefact of ongoing improvements to the BEC and NDT classification systems for southeastern British Columbia. Specifically, the ICHmw4 and ESSFdmw variants and the ESSFdm subzone are relatively new BEC classes, having been created and released in 2005 (pers. comm. D. MacKillop, Ministry of Natural Resource Operations, Nelson, BC). Currently, the ICHmw4 variant is included in NDT2 and the

ESSFdm subzone is included in NDT3. One of six possible corrections to the NDT classification would result in a more logical representation of historical fire frequency:

(1) the ICHmw4 variant is re-classified as NDT3,

(2) the ESSFdm subzone is re-classified as NDT2,

(3) the ICHmw4 variant is re-classified as NDT3 and ESSFdm subzone as NDT2,

(4) the ICHdw1 variant is re-classified as NDT4, ICHmw4 as NDT3, and ESSFdm as NDT2,

(5) the ICHdw1 variant is re-classified as NDT4, ICHmw4 as NDT3, and ESSFdm as NDT2, and

(6) the ICHdw1 variant is re-classified as NDT4, ICHmw4 as NDT4, and ESSFdm as NDT3.

I considered the current classification and all six possible changes for the predicted fire histories in the following analysis.

To assess the accuracy of provincial NDT classes in the study area, I compared observed and predicted fire histories. For the observed fire histories, plots with fire scars were classified as having a stand-maintaining fire regime and fire frequency was represented by the plot-level mean fire return interval (CPFI). Plots without fire scars were classified as having a stand-replacing fire regime. Predicted fire histories were based on the current NDT classes and all possible corrections to the NDT classes. First, I used the forest cover database to determine the BEC unit and current NDT class assigned to each plot. Second, I reclassified each plot by applying each of the six possible combinations of changes to the NDT classes. At the plot scale, the NDT classes determined whether the predicted fire regime included stand-maintaining (NDT4) or stand-replacing (NDT3 and NDT2) fires and the average expected fire return interval (Table 1). For each set of predictions, plots were grouped by NDT classes and the percentage of plots that were accurately classified as having stand-maintaining or stand-replacing fire regimes were calculated. Furthermore, the plots classified as having a stand-replacing fire regime were grouped by NDT class and I compared stand ages (recorded as time-since-last-fire, TSLF) with the predicted mean fire return intervals of 150 years for NDT3 and 200 years for NDT2.

2.3 Results

I observed external fire scars at 25 of the 40 plots, which ranged in elevation from 594 metres above sea level (m.a.s.l.) to 1690 m.a.s.l. (**Table 2.3**). Slope aspect covered the spectrum from 1° to 360°, and steepness ranged from 6° to 33°. In total, 19 plots were situated in northeastern "cooler" aspects (converted aspect <= 90°), and 6 plots were situated in southwestern "warmer" aspects (converted aspect > 90°). Furthermore, only 5 of the plots were in simple topographic slope configurations while the remaining 20 were situated in complex configurations.

Fire-scarred sections were cross-dated from 114 trees, yielding a total of 300 fire-scars (**Table 2.4**). Western larch was most commonly scarred, but scars were also frequent on Douglas-fir and ponderosa pines (**Table 2.5**). In plots with fire scars, more scars were on stumps than trees, snags or logs. Thirteen of the 25 plots were clear-cuts, providing a total of 52 samples from stumps. In the 11 remaining fire history plots, I removed 5 samples from logs, 28 from live trees, and 29 from snags.

One plot, located in the higher elevations, yielded only one fire scar sample, so ten canopy-dominant trees were also cored to determine stand age. Therefore, I extracted 160 cores from cohorts of trees within 16 of the 40 plots (**Table 2.4**).

Table 2.3 Physical characteristics of sample plots in the Darkwoods.

Plot #	Plot Type	UTM		Elevation (m)	Slope			Slope Configuration (Simple or Complex)
		Easting	Northing		Aspect (unconverted °)	Aspect (converted °)	Steepness (°)	
1	Fire History	526063	5447057	727	23	22	19	C
2	Fire History	525344	5447010	980	52	7	29	C
3	Fire History	524485	5447318	997	54	9	26	C
4	Fire History	526066	5448037	594	179	134	6	C
5	Fire History	525624	5447448	788	71	26	20	C
6	Fire History	524797	5448128	765	83	38	10	C
7	Cohort Age	523181	5447677	1592	90	45	28	C
8	Cohort Age	522549	5448057	1626	344	61	13	S
9	Cohort Age	521306	5447896	1639	54	9	24	S
10	Cohort Age	520368	5447908	1812	106	61	10	S
11	Cohort Age	519814	5447639	1850	109	64	29	S
12	Fire History	524077	5449003	768	60	15	22	C
13	Fire History	523754	5448640	1018	70	25	42	S
14	Fire History	522753	5449207	1388	90	45	26	C
15	Mixed	521802	5449159	1651	182	137	8	C
16	Cohort Age	520466	5448968	1747	320	85	33	S
17	Fire History	524582	5449996	616	115	70	22	C
18	Fire History	523514	5449735	900	78	33	18	C
19	Fire History	522553	5449746	1465	86	41	30	C
20	Fire History	521696	5449807	1551	321	84	21	S
21	Fire History	520517	5449762	1403	333	72	29	S
22	Fire History	519312	5449876	1690	152	107	21	C
23	Cohort Age	518825	5449759	1771	158	113	20	C
24	Fire History	523247	5450698	1000	358	47	22	C
25	Fire History	522709	5450932	1040	70	25	33	C
26	Fire History	521869	5450759	1210	353	52	26	S
27	Fire History	520738	5450519	1423	110	65	28	S
28	Cohort Age	519701	5450908	1683	10	35	27	S
29	Cohort Age	518864	5450903	1714	322	83	18	C
30	Cohort Age	517865	5450894	1790	4	41	15	S
31	Cohort Age	516716	5451213	1869	98	53	4	S
32	Fire History	522630	5451793	794	188	143	31	C
33	Fire History	521705	5452220	1158	146	101	16	C
34	Fire History	520554	5452313	1392	147	102	20	C
35	Cohort Age	519040	5451850	1654	148	103	20	S
36	Cohort Age	518157	5451956	1817	135	90	27	C
37	Cohort Age	517313	5451761	1812	342	63	8	S
38	Cohort Age	516455	5451783	1844	307	98	20	S
39	Fire History	520204	5452521	1512	106	61	10	C
40	Fire History	520201	5453812	1500	68	23	11	C
			Mean:	1363.8	151.1	62.2	21.1	-
			Median:	1482.5	109.5	61	21	-
			Min:	594	4	7	4	-
			Max:	1869	358	143	42	-

Table 2.4 Overview of fire-scarred cookies and cores sampled to quantify the fire history of 40 plots within the Darkwoods.

Plot #	Cookies	Cores	Elevation (m)
1	3	-	727
2	5	-	980
3	5	-	997
4	4	-	594
5	5	-	788
6	5	-	765
7	-	10	1592
8	-	10	1626
9	-	10	1639
10	-	10	1812
11	-	10	1850
12	5	-	768
13	5	-	1018
14	4	-	1388
15	1	10	1651
16	-	10	1747
17	5	-	616
18	4	-	900
19	5	-	1465
20	4	-	1551
21	2	-	1403
22	5	-	1690
23	-	10	1771
24	5	-	1000
25	5	-	1040
26	5	-	1210
27	5	-	1423
28	-	10	1683
29	-	10	1714
30	-	10	1790
31	-	10	1869
32	5	-	794
33	5	-	1158
34	6	-	1392
35	-	10	1654
36	-	10	1817
37	-	10	1812
38	-	10	1844
39	7	-	1512
40	4	-	1500
Total	114	160	

Table 2.5 Overview of fire-scarred trees by species and condition.

Species *	Sample Count	Condition **	Count	1 Scar	2+ Scars
Py	18	T	8	1	7
		Sn	6	0	6
		St	3	1	2
		L	1	0	1
			Total	2	16
Fd	11	T	0	0	0
		Sn	0	0	0
		St	10	4	6
		L	1	0	1
			Total	4	7
Lw	85	T	20	7	13
		Sn	23	5	18
		St	39	15	24
		L	3	1	2
			Total	28	57
			Sub-Total:	34	80

Total of 114 firescar samples.

* Py = ponderosa pine (*Pinus ponderosa*)
Fd = interior Douglas-fir (*Pseudotsuga menziesii var. glauca*)
Lw = western larch (*Larix occidentalis*)

** T = Live Tree
Sn = Snag
St = Stump
L = Log

2.3.1 Fire History

Low- and moderate-severity fires were frequent in the study area between 1703 and 1966. At the tree-level, MPFI, compared across the study area, varied from 3 to 147 years, with a mean return interval of 40 years and a WMPI of 32.7 years. At the plot-level, fire intervals varied from 3 to 128 years, with a mean return interval (CPFI) of 33.1 years and a WMPI of 27.7 years (**Table 2.6**). Medium sized, low- to moderate-severity fires (>10% scarred) occurred in four separate years: 1703, 1795, 1866 and 1889. Large fires (>25% scarred), occurred in five separate years: 1718, 1768, 1823, 1831 and 1886. The largest, most widespread fires (>50% scarred) occurred in 1739, 1869 and 1904 (**Figure 2.6**). Across the watershed, CWFI ranged between 1 and 28 years, with a mean return interval of 7.3 years and a WMPI of 5.3 years.

Table 2.6 Summary of fire history statistics for 25 of 40 plots that included fire-scarred trees. The fire recording periods include the year of the first fire scar to death of last recording tree. All statistics are for the time period between 1690 and 2010, and include all scarred trees.

Plot #	Fire Recording Period	Sample size (n)			Fire intervals (years)			
		Fire-scarred samples	Fire scars	Fire intervals	Range	CPFI	WMPI	TSLF
1	1696 - 2010	3	12	3	15 - 43	27	26.44	106
2	1752 - 2010	5	16	5	6 - 43	20.8	18.7	83
3	1737 - 2008	5	14	4	3 - 25	16.5	15.22	121
4	1703 - 2010	4	15	5	20 - 84	37.2	34.09	121
5	1695 - 2010	5	11	2	23 - 43	33	N/A	121
6	1824 - 1981	5	6	2	18 - 36	27	N/A	106
12	1826 - 2004	5	6	1	18	18	N/A	106
13	1772 - 2003	5	13	5	7 - 80	34.2	27.63	44
14	1718 - 2010	4	12	6	17 - 46	28	27.74	124
15	1776 - 2010	1	1	0	N/A	N/A	N/A	141
17	1815 - 2010	5	12	2	25 - 56	40.5	N/A	106
18	1744 - 1974	4	10	5	3 - 55	21.8	16.1	106
19	1690 - 1989	5	17	7	8 - 84	32.29	28.11	66
20	1690 - 2010	4	6	2	38 - 95	66.5	N/A	46
21	1848 - 1971	2	2	1	35	35	N/A	106
22	1690 - 2007	5	8	4	15 - 77	36.25	32.81	101
24	1748 - 1996	5	13	2	18 - 55	36.5	N/A	106
25	1739 - 2010	5	15	7	5 - 56	28.43	26.13	72
26	1690 - 2005	5	13	4	17 - 63	32.5	30.65	141
27	1768 - 2010	5	10	2	26 - 75	50.5	N/A	141
32	1739 - 1986	5	18	6	13 - 63	33.3	31.2	71
33	1756 - 2010	5	17	6	16 - 63	30.17	28.4	90
34	1690 - 1975	6	11	3	8 - 128	50.67	30.82	90
39	1690 - 2007	7	14	6	6 - 101	32.83	25.76	95
40	1690 - 2010	4	5	3	11 - 38	24.3	23.7	106
Summary								
All	1690 - 2010	114	277	93	3 - 128	33.1	27.7	44

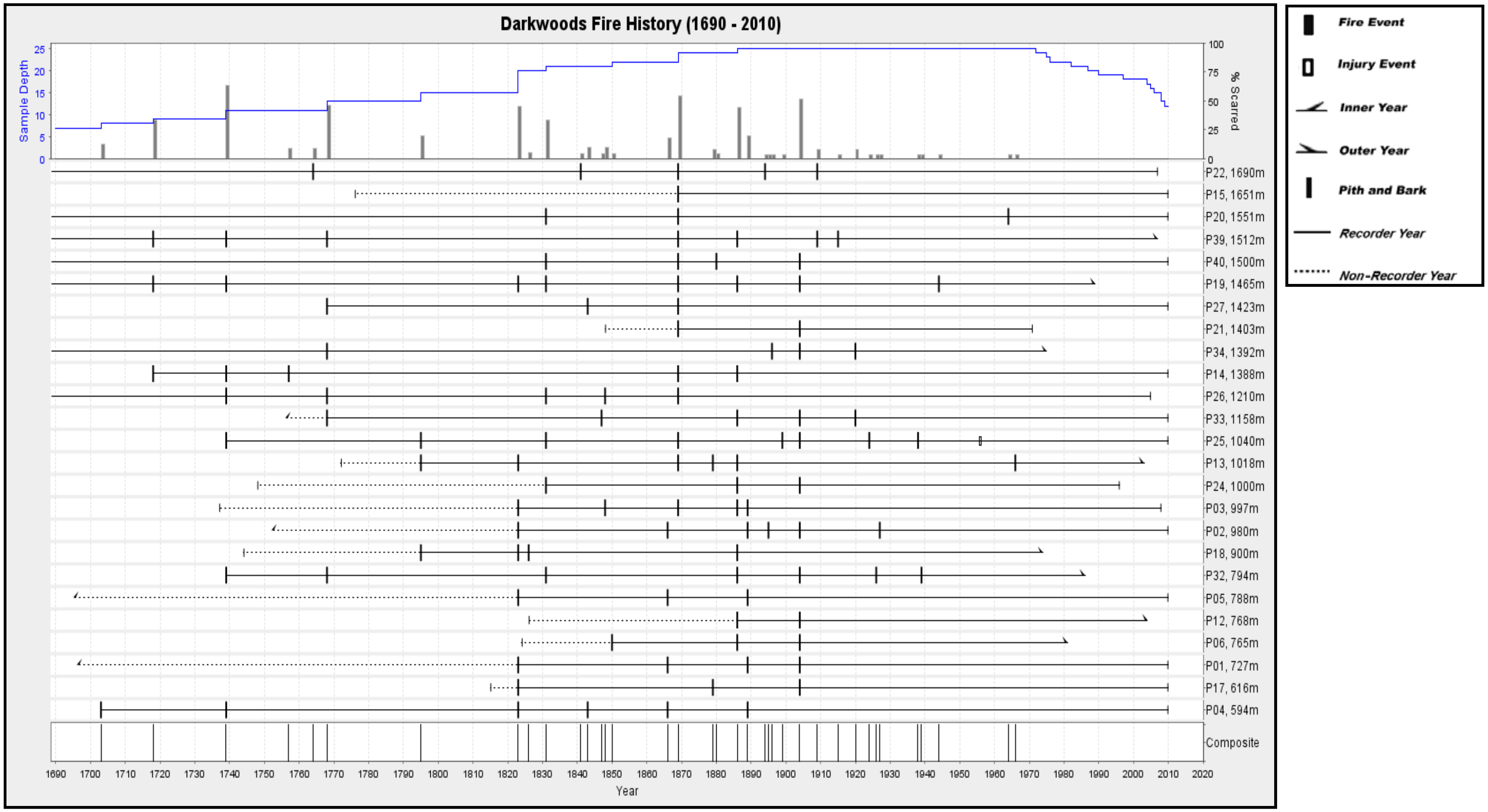

Figure 2.6 Fire history for sample plots within the study area. Plots are arranged by elevation, from lowest (bottom) to highest (top). The top chart shows sample depth (blue line) and the percentage of samples with scars (black bars) over time. The bottom chart shows the composited fire history for the entire study area.

In all but four of the tree cohort plots, stand establishment took place between the early-1870s and mid-1880s. Compared with dates from adjacent fire-scar samples, this implies the last stand-replacing, high-severity fire to reach the higher elevations was likely the widespread 1869 fire. The remaining four plots, located in the far northwest portion of the study area, established in the late 1520s (n= 1), the 1640s (n = 2) and the mid-1930s (n = 1) (**Figure 2.7**).

WMPI could not be calculated for 9 of the 26 fire history plots due to an inadequate number of fires (n < 3), and subsequent lack of return intervals (n < 2). However, FFI exceeded WMPI in all plots where WMPI could be calculated (n = 16; **Table 2.6**).

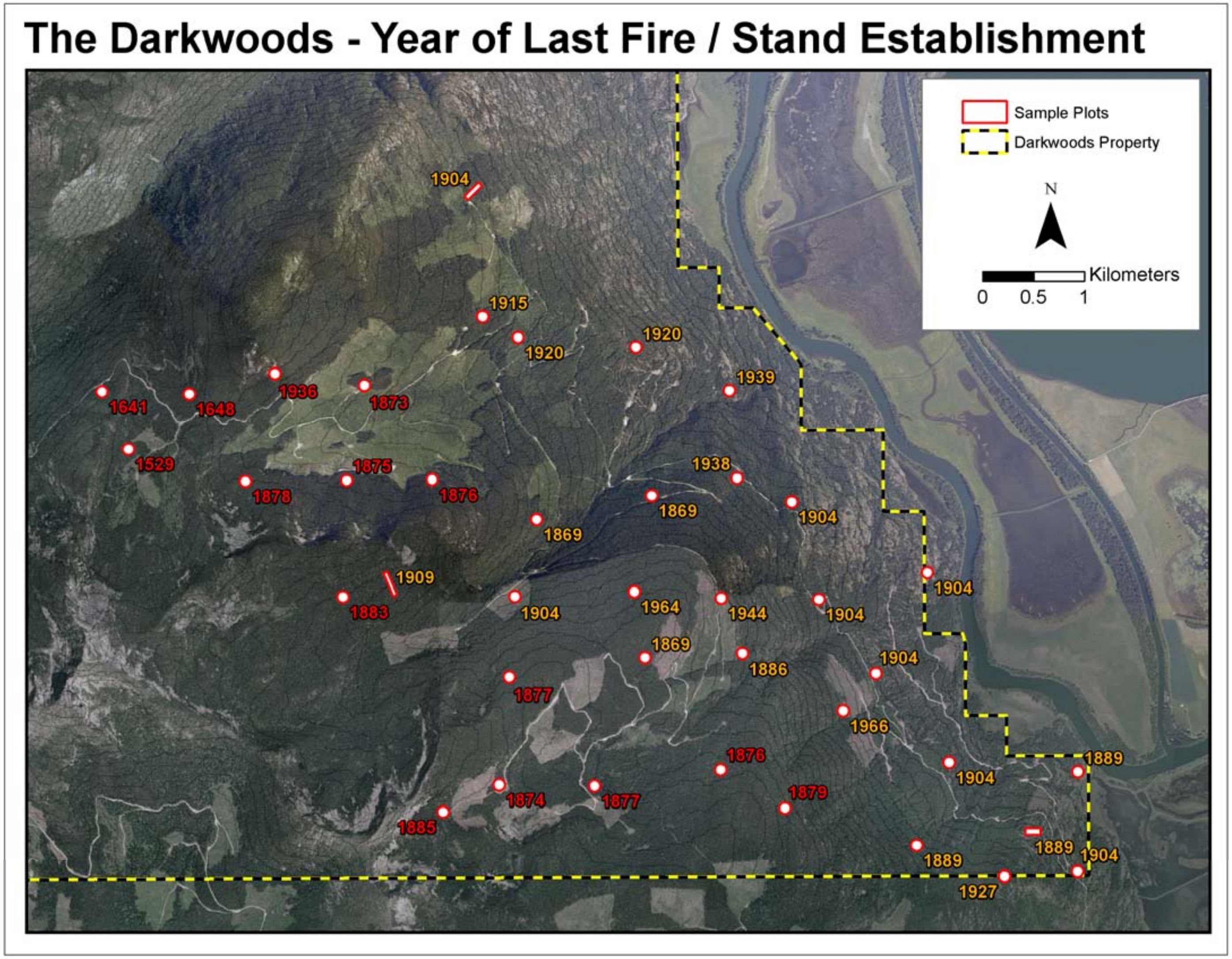

Figure 2.7 The year of the last fire, in orange, and year of stand establishment, in red.

2.3.2 Spatio-Temporal Variation

2.3.2.1 Tree-Level Variability

At the tree-level, the likelihood of fire occurrence varied significantly with elevation (β= -0.0025 ± 0.0003, P<0.0001), slope aspect (β= -0.0069 ± 0.0020, P=0.0006), and slope steepness (β= 0.0205 ± 0.0079, P=0.0095) (**Table 2.7**). The negative coefficients of elevation and slope aspect in the models of fire log odds ratios (**Table 2.7**) indicate the likelihood of fire decreased with increasing elevation and increasingly warmer aspects. The positive coefficient of slope steepness in all models of fire log odds ratios indicates fire was more likely to occur in steeper slopes.

Anthropogenic influences on the fire regime varied significantly between periods of land-use (P=0.0397); however, a strong interaction between slope aspect and the periods of land-use was also identified (P=0.0076). By extension, this implies aspect altered the modeled slopes for each of the periods, affecting the degree to which the likelihood of fire occurrence varied throughout each period. Asymptotic z-tests and the model of fire log odds ratio (M_F) results indicated fire occurrence in Period IV, the period of modern fire suppression (1930 to 2010), was less likely (α_{MF} = -11.51, P=<0.0001) when compared with the control period (Period II, α_{MF} = -1.45). Compared with Period II, fires were slightly more likely to occur in Period I (α_{MF} = -0.65) but not significantly so (P=0.3900) and fires were more likely to occur in = Period III (α_{MF} = -2.23) but differences were also not significant (P=0.1147).

The aspect interaction with period influenced the slope but not the intercept of the models for fire log odds ratios. Overall, increasingly warmer aspects resulted in negative modeled slopes in each model of fire log odds ratios (**Table 2.7**). However, asymptotic z-tests indicate that only the interaction of slope aspect with Periods III and IV were significantly different from the aspect interaction with Period II ($P=0.0018$ and $P=0.0436$, respectively). Though the coefficients were small, the positive influence of aspect interactions with Period III and Period IV indicate fires were more likely to occur in warmer aspects than they did in Period II. Aspect x Period I did not differ significantly from Aspect x Period II, indicating a similar likelihood of fire throughout the pre-Euro-American settlement periods regardless of aspect.

Table 2.7 Tree-level effects of topography and differences in anthropogenic land-use on the occurrence of fire. Type 3 score statistics compare the significance of variables and interactions relative to all other variables in the model, providing overall significance values. Asymptotic z-tests determine the significance of individual coefficient estimates.

Effect			Type 3 Score Statistics	Asymptotic Z-Tests			
			P-value	β_i	SE	95% CI	*P*-value
α	intercept		-	-1.4447	0.4393	(-2.3058, -0.5836)	0.0010
X_1	elevation		<0.0001	-0.0025	0.0003	(-0.0030, -0.0019)	<0.0001
X_2	aspect_lin		0.0127	-0.0069	0.0020	(-0.0109, 0.0030)	0.0006
X_3	steepness		0.0070	0.0205	0.0079	(0.0050, 0.0361)	0.0095
X_{4a}	Period I			0.7994	0.9299	(-1.0231, 2.6219)	0.3900
X_{4b}	Period III		0.0397	-0.7863	0.4984	(-1.7631, 0.1906)	0.1147
X_{4c}	Period IV			-10.0652	2.3567	(-14.6843, 5.4460)	<0.0001
X_{5a}		Period I		-0.0004	0.0004	(-0.0012, 0.0005)	0.3775
X_{5b}	elevation x	Period III	0.2866	0.0002	0.0003	(-0.0004, 0.0008)	0.5417
X_{5c}		Period IV		0.0012	0.0005	(0.0002, 0.0022)	0.0200
X_{6a}		Period I		-0.0027	0.0045	(-0.0116, 0.0062)	0.5504
X_{6b}	aspect_lin x	Period III	0.0076	0.0070	0.0023	(0.0026, 0.0114)	0.0018
X_{6c}		Period IV		0.0130	0.0064	(-0.0004, 0.0256)	0.0436
X_{7a}		Period I		0.0185	0.0163	(-0.0135, 0.0505)	0.2567
X_{7b}	steepness x	Period III	0.5409	0.0052	0.0099	(-0.0142, 0.0246)	0.5976
X_{7c}		Period IV		0.1400	0.0895	(-0.0355, 0.3155)	0.1180
Model fit statistics							
	Convergence Criteria Met?		Yes				
	QIC		2750.3101				
	QICu		2763.3006				

Model of fire log odds ratio (M_F)

$M_F = \alpha_{MF} + (\beta_1)^*X_1 + (\beta_2)^*X_2 + (\beta_3)^*X_3 + (\beta_{4a})^*X_{4a} + (\beta_{4b})^*X_{4b} + (\beta_{4c})^*X_{4c} + (\beta_2 + \beta_{6a})^*(X_2^*X_{4a}) + (\beta_2 + \beta_{6b})^*(X_2^*X_{4b}) + (\beta_2 + \beta_{6c})^*(X_2^*X_{4c})$

= -1.4447 - (0.0025)*elevation - (0.0069)*aspect_lin + (0.0205)*steepness + (0.7994)*Period1 - (0.7863)*Period3 - (10.0652)*Period4 + (-0.0069 -0.0027)*(aspect_lin*Period1) + (-0.0069 + 0.0070)*(aspect_lin*Period3) + (-0.0069 + 0.0130)*(aspect_lin*Period4)

= -1.4447 - (0.0025)*elevation - (0.0069)*aspect_lin + (0.0205)*steepness + (0.7994)*Period1 - (0.7863)*Period3 - (10.0652)*Period4 - (0.0096)*(aspect_lin*Period1) + (0.0001)*(aspect_lin*Period3) + (0.0061)*(aspect_lin*Period4)

For Period = I (Period I = 1, Period II = 0, Period IV = 0):
M_F = -0.65 - (0.0025*elevation) - (0.0165)*aspect_lin + (0.0205)*steepness

For Period = II (Period I = 0, Period III = 0, Period IV = 0):
M_F = -1.45 - (0.0025)*elevation - (0.0064)*aspect_lin + (0.0205)*steepness

For Period = III (Period I = 0, Period III = 1, Period IV = 0):
M_F = -2.23 - (0.0025)*elevation - (0.0063)*aspect_lin + (0.0205)*steepness

For Period = IV (Period I = 0, Period III = 0, Period IV = 1):
M_F = -11.51 - (0.0025)*elevation - (0.0008)*aspect_lin + (0.0205)*steepness

2.3.2.2 Plot-Level Variability

At the plot-level, the likelihood of fire occurrence varied significantly with elevation (β= -0.0014 ± 0.0003, P=0.0072; **Table 2.8**), with the negative coefficient indicating fire likelihood decreased with increasing elevation. However, the likelihood of fire did not vary significantly with slope aspect (P=0.1259) or slope steepness (P=0.1568). Furthermore, anthropogenic influences on the fire regime between periods of land-use were not significant (P=0.3493), nor were any of the interactions between the continuous and class variables (all P-values for interactions >= 0.3277).

Table 2.8 Plot-level effects of topography and differences in anthropogenic land-use on the occurrence of fire. Type 3 score statistics compare the significance of variables and interactions relative to all other variables in the model, providing overall significance values. Asymptotic z-tests determine the significance of individual coefficient estimates.

Effect			Type 3 Score Statistics	Asymptotic Z-Tests			
			P-value	β_i	SE	95% CI	*P*-value
α	intercept		-	-2.5098	0.5153	(-3.5199, -1.4998)	<0.0001
X_1	elevation		0.0072	-0.0014	0.0003	(-0.0021, -0.0008)	<0.0001
X_2	aspect_lin		0.1259	-0.0079	0.0027	(-0.0132, 0.0027)	0.0031
X_3	steepness		0.1568	0.0267	0.0143	(0.0013, 0.0547)	0.0615
X_{4a}	Period I			-0.5925	0.8843	(-2.3258, 1.1407)	0.5028
X_{4b}	Period III		0.3493	-0.4936	0.6191	(-1.7071, 0.7200)	0.4254
X_{4c}	Period IV			-5.0240	3.0080	(-10.9195, 0.8715)	0.0949
X_{5a}		Period I		0.0001	0.0004	(-0.0007, 0.0009)	0.8511
X_{5b}	elevation x	Period III	0.7811	0.0003	0.0004	(-0.0004, 0.0011)	0.3961
X_{5c}		Period IV		0.0008	0.0011	(0.0014, 0.0029)	0.4752
X_{6a}		Period I		0.0076	0.0042	(-0.0005, 0.0158)	0.0670
X_{6b}	aspect_lin x	Period III	0.3277	0.0086	0.0041	(0.0005, 0.0166)	0.0382
X_{6c}		Period IV		0.0130	0.0106	(0.0078, 0.0338)	0.2208
X_{7a}		Period I		0.0218	0.0278	(-0.0326, 0.0762)	0.4327
X_{7b}	steepness x	Period III	0.6421	-0.0063	0.0220	(-0.0494, 0.0368)	0.7750
X_{7c}		Period IV		0.0402	0.0628	(-0.0830, 0.1633)	0.5228
Model fit statistics							
	Convergence Criteria Met?		Yes				
	QIC		1317.592				
	QICu		1327.7075				

Model of fire log odds ratio (M_F)

$$M_F = \alpha + (\beta_1)*X_1$$
$$= -2.5098 - (0.0014)*\text{elevation}$$

2.3.3 Provincial NDT Classes

As the current NDT classes are defined, four plots were designated as NDT4, 28 as NDT3 and eight as NDT2 (**Table 2.9**). Plots in the ICHxw subzone and designated as NDT4 were appropriately classified as stand-maintaining fires in all NDT classification configurations (predicted = observed = 100%; mean return intervals between 4 – 50 yrs; **Table 2.10**). The 10 plots in the ICHdw1 variant are currently classified as NDT3 and the 8 plots in the ICHmw4 variant are currently classified as NDT2; however, all 18 plots had fire scars indicating occurrence of low- to moderate-severity fires and misclassification of the historic fire regime. They would be more accurately classified as NDT4, making option 6 for revisions to the NDT classes most accurate. Of the 18 plots in the ESSFdm subzone, two had fire scars and 16 last burned by stand-replacing fires. In options 3, 4 and 6, the ESSFdm subzone was separated from other BEC units, resulting in the highest percentage of observed stand-replacing fires (89%). In options 3 and 4, the ESSFdm subzone was classified as NDT2, which has a mean fire return interval of 200 years. In option 6, the ESSFdm subzone was classified as NDT3, which has a mean fire return interval of 150 years.

Stand ages (denoted as TSLF in **Table 2.9**) for plots in the ESSFdm subzone ranged from 74 to 481 years, with a 67th percentile of 136 years. If I assume that the age distribution of the sampled stands is representative of their proportion in the landscape, then the estimated fire return interval would be 136 years and the ESSFdm subzone is best classified as NDT3. In this interpretation, the current classification of the ESSFdm subzone is appropriate.

Table 2.9 Plot-level observed and predicted fire histories. Observed fire histories include whether scars were present on the plot, the composite plot-level fire return interval (CPFI), and the time since last fire (TSLF). TSLF is in years since the last fire for plots with fire scars, and represents the cohort age in plots without fire scars. The predicted fire histories include the BEC zone designation for each plot (BEC Unit) and all corresponding configurations of NDTs, including the present arrangement of NDT classes (Current), and the six configuration options assessed in this study (Option 1 – Option 6).

Plot #	Observed Fire History			Predicted Fire History							
	Scars Present	CPFI (years)	TSLF (years)	BEC Unit	NDT Class						
					Current	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
1	Yes	27.0	106	ICHxw	4	4	4	4	4	4	4
2	Yes	20.8	83	ICHdw1	3	3	3	3	4	4	4
3	Yes	16.5	121	ICHdw1	3	3	3	3	4	4	4
4	Yes	37.2	121	ICHxw	4	4	4	4	4	4	4
5	Yes	33.0	121	ICHdw1	3	3	3	3	4	4	4
6	Yes	27.0	106	ICHdw1	3	3	3	3	4	4	4
7	No	-	134	ESSFdm	3	3	2	2	2	3	3
8	No	-	131	ESSFdm	3	3	2	2	2	3	3
9	No	-	133	ESSFdm	3	3	2	2	2	3	3
10	No	-	136	ESSFdm	3	3	2	2	2	3	3
11	No	-	125	ESSFdm	3	3	2	2	2	3	3
12	Yes	18.0	106	ICHdw1	3	3	3	3	4	4	4
13	Yes	34.2	44	ICHdw1	3	3	3	3	4	4	4
14	Yes	28.0	124	ICHmw4	2	3	2	3	3	3	4
15	Yes	-	141	ESSFdm	3	3	2	2	2	3	3
16	No	-	133	ESSFdm	3	3	2	2	2	3	3
17	Yes	40.5	106	ICHxw	4	4	4	4	4	4	4
18	Yes	21.8	106	ICHdw1	3	3	3	3	4	4	4
19	Yes	32.3	66	ICHmw4	2	3	2	3	3	3	4
20	Yes	66.5	46	ESSFdm	3	3	2	2	2	3	3
21	Yes	35.0	106	ICHmw4	2	3	2	3	3	3	4
22	Yes	36.3	101	ESSFdm	3	3	2	2	2	3	3
23	No	-	127	ESSFdm	3	3	2	2	2	3	3
24	Yes	36.5	106	ICHdw1	3	3	3	3	4	4	4
25	Yes	28.4	72	ICHdw1	3	3	3	3	4	4	4
26	Yes	32.5	141	ICHmw4	2	3	2	3	3	3	4
27	Yes	50.5	141	ICHmw4	2	3	2	3	3	3	4
28	No	-	134	ESSFdm	3	3	2	2	2	3	3
29	No	-	135	ESSFdm	3	3	2	2	2	3	3
30	No	-	132	ESSFdm	3	3	2	2	2	3	3
31	No	-	481	ESSFdm	3	3	2	2	2	3	3
32	Yes	33.3	71	ICHxw	4	4	4	4	4	4	4
33	Yes	30.2	90	ICHdw1	3	3	3	3	4	4	4
34	Yes	50.7	90	ICHmw4	2	3	2	3	3	3	4
35	No	-	137	ESSFdm	3	3	2	2	2	3	3
36	No	-	74	ESSFdm	3	3	2	2	2	3	3
37	No	-	362	ESSFdm	3	3	2	2	2	3	3
38	No	-	369	ESSFdm	3	3	2	2	2	3	3
39	Yes	32.8	95	ICHmw4	2	3	2	3	3	3	4
40	Yes	24.3	106	ICHmw4	2	3	2	3	3	3	4

Table 2.10 Assessment of the natural disturbance type (NDT) classes. Data includes the NDT classification arrangements assessed in this study (NDT Classification), the NDT classes assigned to each configuration (NDT), the associated configuration of BEC zones (BEC Units), the number of plots within each predicted NDT class (N), as well as the calculated percentages of plots designated as stand-maintaining or stand-replacing fires, based on the predicted and observed fire behavior.

NDT Classification	NDT	BEC Units	N	Stand Maintaining Fires			Stand-replacing Fires	
				Predicted (%)	Observed (%)	CPFI Range (years)	Predicted (%)	Observed (%)
Current	4	ICHxw	4	100	100	27.0 - 40.5	0	0
	3	ICHdw1, ESSFdm	28	0	43	16.5 - 66.5	100	57
	2	ICHmw4	8	0	100	24.3 - 50.7	100	0
Option 1	4	ICHxw	4	100	100	27.0 - 40.5	0	0
	3	ICHdw1, ICHmw4, ESSFdm	36	0	56	16.5 - 66.5	100	44
	2	-	0	0	-	-	100	-
Option 2	4	ICHxw	4	100	100	27.0 - 40.5	0	0
	3	ICHdw1	10	0	100	16.5 - 36.5	100	0
	2	ICHmw4, ESSFdm	26	0	38	24.3 - 66.5	100	62
Option 3	4	ICHxw	4	100	100	27.0 - 40.5	0	0
	3	ICHdw1, ICHmw4	18	0	100	16.5 - 50.7	100	0
	2	ESSFdm	18	0	11	36.3 - 66.5	100	89
Option 4	4	ICHxw, ICHdw1	14	100	100	16.5 - 40.5	0	0
	3	ICHmw4	8	0	100	24.3 - 50.7	100	0
	2	ESSFdm	18	0	11	36.3 - 66.5	100	89
Option 5	4	ICHxw, ICHdw1	14	100	100	16.5 - 40.5	0	0
	3	ICHmw4, ESSFdm	26	0	38	24.3 - 66.5	100	62
	2	-	0	0	-	-	100	-
Option 6	4	ICHxw, ICHdw1, ICHmw4	22	100	100	16.5 - 50.7	0	0
	3	ESSFdm	18	0	11	36.3 - 66.5	100	89
	2	-	0	0	-	-	100	-

2.4 Discussion

2.4.1 Fire History

The full spectrum of fire severities occurred in the study area, with low- and moderate-severity fires reconstructed from fire-scar samples and high-severity fires reconstructed from tree cohort ages. Therefore, the fire regime for the entire study area is classified as mixed-severity. Frequencies of low- and moderate-severity fires are similar to other studies in mixed-severity fire regimes in southeastern B.C. (Cochrane 2007, Da Silva 2009), although the mean (33.1 yr) and Weibull median (27.7 yr) CPFI were shorter for the Darkwoods than for montane forests in the southern Rocky Mountain Trench (mean CPFI = 48.3 yr, WMPI = 40.8 yr; Cochrane 2007), but they nearly mirror those of the Joseph and Gold Creek watersheds in the east Kootenays (mean CPFI = 35.8 yr, WMPI = 29.2 yr; Da Silva 2009).

FFI exceeded all calculated WMPI among plots, a finding common among studies in southeastern British Columbia (Cochrane 2007, Da Silva 2009, Nesbitt 2010), though to varying degrees. Nevertheless, my findings indicate a strong fire exclusion effect, though the impact on forest structures is not fully understood. A full stand dynamics assessment will be necessary in order to assess the degree to which fire exclusion has altered the forests of the Darkwoods.

2.4.2 Spatio-Temporal Variation

2.4.2.1 Tree-Level Variability

2.4.2.1.1 Fire Likelihood Varied By Elevation, Slope Aspect and Steepness

The relationship between decreased likelihood of fire occurrence with increasing elevation is consistent with previous studies in southeastern BC (Cochrane 2007, Nesbitt 2010). Elevation probably influences fuel moisture levels directly, and indirectly affects fuel types (Heyerdahl et al. 2001). In general, moisture levels and moisture duration throughout the year increase with elevation in the Darkwoods; the higher elevations are cooler and more mesic, as snow pack persists until mid- to late-spring, and summer thunderstorms typically bring high levels of rain to the upper elevations (Environment Canada 2010). Fuel type also varies with elevation; the lowest elevations support sparse, open forests that generate abundant, well-aerated fine fuels on the forest floor that facilitate the spread of surface fires (Swetnam and Baisan 1996), while the highest elevations support dense, subalpine forests that generate short, stout-needled fuels that compact tightly on the forest floor, inhibiting the spread of fire (Swetnam and Baisan 1996). Therefore, natural moisture barriers and fuel types prevent the spread of fire to higher elevations for most of the year, at least while wetter and cooler climatic conditions prevail (Heyerdahl et al. 2001, Schoennagel et al. 2004).

Fire occurrence varying significantly with slope aspect is consistent with previous fire history studies in southeastern BC (Heyerdahl et al. 2007), but the decreasing likelihood of fire with increasingly warmer aspects is uncommon. Cochrane (2007) found fires to be more frequent in plots with northern aspects than plots with southern aspects, and attested this to either (1) a higher frequency of fires that resulted in intensities that were too low to scar trees, or (2) that aspect was not a strong determinate of fire frequency in the montane forests of southeastern B.C. Though the former scenario seemed plausible, he observed fire scars on both warm and cool aspects and documented larger variation in fire frequency among plots rather than between aspect strata, and settled on the latter scenario as the more likely of the two. I did not test for specific differences between aspect strata in this study, but this could also be the case for the occurrence of fire in the forests of the Darkwoods. In my study area, significant differences between fire frequencies in "cooler" versus "warmer" aspects could also reflect the general east-northeast aspect of the watershed, which directly biases forest aspects in favour of more northeastern aspects. I obtained fire-scar samples from 19 plots with northern, "cooler" aspects, as opposed to six plots with southern, "warmer" aspects. Given sampling took place within a systematic grid, had the slopes been more evenly distributed between northern and southern aspects, plot biophysical characteristics would likely reflect an equal distribution between northern and southern facing aspects. Future analyses of potential spatial controls of historic fire regimes in southeastern B.C. should either (1) include a broad range of aspects with equal representation in the sample set, (2) attempt to stratify the sample set by cool and warm aspects to accurately capture its effect on the variation of fire occurrence, or (3) not include aspect as a potential spatial control of forest fires if the range of values is limited.

Slope steepness was also important in explaining spatial variation in fire occurrence at the tree-level. Slope steepness, in conjunction with increasing elevation, affects fire directly; steeper slopes preheat fuels through radiant and convective heating (Agee 1993), resulting in increased fire intensity and rate of spread as compared to gentle slopes (Albini 1976, Rothermel 1983, Heyerdahl 2001). In areas dominated by low-severity fires, a higher degree of steeper slopes may increase the intensity of fires so that critical temperatures are reached, causing cambial damage and subsequent fire-scars to form. Alternatively, in areas experiencing more severe fires, steeper slopes may result in a higher degree of above-ground vegetative mortality, removing potential recorders of fire from the record. Despite the potential effects of the latter scenario, slope configuration can also influence the survivability of trees. Complex slope configurations induce micro-climatic controls on fire behaviour, altering the amount and condition of fuels indirectly (Heyerdahl et al. 2007). This, in turn, can favour the survivability of trees, as fire intensity becomes variable. On the other hand, simple slope configurations allow fire to move unhindered. Depending on other attributes such as slope steepness and stand structure, simple slopes can generate more severe fire behaviour, facilitating the removal of potential recorders of fire from the landscape. Of the 25 fire history plots in this study, 17 were situated in slopes of 20° or greater, and four of these plots were steeper than 30°. However, 20 of the 25 fire history plots were situated on slopes with complex topography, indicating a potential link between complex slope configurations and the likelihood of fire occurrence in steeper slopes.

2.4.2.1.2 Fire Likelihood Varied By Anthropogenic Influences and Interactions with Slope Aspect

The anthropogenic influence on the likelihood of fire occurrence is apparent in the southeastern-most watershed of the Darkwoods. While my findings are consistent with other studies in southeastern B.C. that found no significant differences between periods of land-use prior to Euro-American settlement (i.e., Period I and Period II; Cochrane 2007, Da Silva 2009, Nesbitt 2010), only Da Silva (2009) also found no significant difference in fire occurrence during the period of Euro-American Settlement. Compared with pre-Euro-

American settlement trends, Cochrane (2007) and Nesbitt (2010) found fires to be significantly more frequent after Euro-American settlement commenced in the 1850s. However, different results for the Euro-American settlement period between studies are expected because settlement rates and land-use patterns likely differed across the region. Though attempts to suppress fires during this period inevitably occurred and were perhaps effective in preventing the spread of the lowest severity fires, without modern tools and methods of fire suppression, fire occurrence would have remained consistent with pre-settlement frequencies, or perhaps increased due to the use of fire as a tool for clearing land (Veblen et al. 2000). Alternatively, as Euro-American settlers arrived in the region in the late 1800s, any pre-existing First Nations use of fire to manage the land would have been diminished or removed entirely as they became unseated from their land tenure (Ktunaxa Nation 2005), reducing the occurrence of fire in the landscape. Any combination of these settlement-era effects can result in entirely different fire histories between study areas.

The significant difference between the control period and the modern fire suppression period (Period IV: 1945-2010) indicates a likely correlation between modern methods of fire suppression and the reduction in fire occurrence during the 20th century. Though this finding is consistent with other studies in southeastern BC (Cochrane 2007, Da Silva 2009, Nesbitt 2010), understanding the relationships between climate and fire on inter-annual to decadal scales is important to differentiate human-induced variation in the fire regime from climatically-induced variation in the fire regime (Daniels et al. 2011).

Significant differences in the occurrence of fire between interactions of slope aspect with periods of anthropogenic land-use highlight the degree to which slope aspect alters the likelihood of fire events throughout each period. Overall, fires were most likely to occur in cooler aspects, though fires in Period III and Period IV were significantly more likely to occur in increasingly warmer aspects compared to the pre-Euro-American settlement era. These findings may indicate an alteration in the fire regime as settlers began to occupy and use the lands adjacent to the Darkwoods property, particularly in and around the town of Creston, which lies directly southwest from the property. However, these results may also reflect an increasing effect of post-industrial era climate change in B.C. (Daniels et al. 2011), as southern aspects may be heating up and drying out more so than pre-industrial conditions would allow. A climate analysis using methods such as superposed epoch analysis (SEA) will be necessary to tease out such interactions between fire and climate.

2.4.2.2 Plot-Level Variability

2.4.2.2.1 Fire Likelihood Varied By Elevation

At the plot-level, elevation was the only significant effect on the likelihood of fire, placing elevation as the dominant control of fire occurrence in the southeastern watershed of the Darkwoods. Other studies in southeastern B.C. have likewise found elevation to be the most important spatial control on fire occurrence (Cochrane 2007, Nesbitt 2010). Elevation controls the magnitude and duration of numerous microclimatic factors, such as solar insolation, temperature and precipitation. In conjunction with soil, these microclimatic factors determine the suitability of growing conditions for plant species, directly affecting the both fuel condition and fuel type (Heyerdahl et al. 2007). Given the distinct forest structures and configurations across the elevational gradient, from the more sparse and open ponderosa pine and Douglas-fir forests in the lowest elevations to the dense Engelmann spruce and subalpine fir forests in the highest elevations, the influence of elevation in this study area is visibly apparent.

2.4.2.3 Tree-Level Versus Plot-Level Variability

The differences in spatial and spatio-temporal controls on the occurrence of fire between tree-level and plot-level analyses are striking. Tree-level variation is greatly influenced by bottom-up, micro-site controls, reflecting the complex topographic nature of the study area, and the degree to which microclimate affects heterogeneity in individual fires within the watershed. Furthermore, tree-level variation in fire occurrence was significantly different during the modern fire suppression period, indicating the number of fires have been greatly reduced since the 1940s. Broader plot-level variation in fire likelihood is controlled solely by elevation, reflecting the characteristics of the fire regimes that dominate from the valley floor to ridge tops. Fire histories reveal that a majority of the forests of the Darkwoods are outside their historic range of variability, making them highly susceptible to more severe fire behaviour in the future. Management decisions must consider these factors across multiple scales, particularly with intentions of conserving or restoring habitat for specific wildlife species, or to maintain healthy, sustainable forests for ulterior purposes, such as carbon sequestration.

2.4.3 Provincial NDT Classes

2.4.3.1 Assessment of Current NDT Classes

As the current provincial NDT classification schema is defined, there are two systematic errors in the representation of historic fire disturbances in the Darkwoods. The first error is the over-representation of stand-replacing fires at mid-elevations. All plots in the ICH zone had observed fire histories that included fire scars from low- to moderate-severity fires but 18 of the 22 plots were inaccurately classed as having stand-replacing fire regimes (e.g., currently classified as NDT2 or NDT3). Furthermore, the five of six options, applied here as potential corrections for the NDT classes in the study area, failed to accurately classify these 18 plots. Only option 6, in which all plots in the ICH zone were classified as NDT4, accurately represented the predominantly low- to moderate severity fires.

A second systematic error is an under-representation of the range of intervals between successive low- to moderate-severity fires. While the predicted range of fire intervals (4-50) is consistent with the observed means, it does not account for the full range of variation. Given that several of the misclassified fire history plots have CPFI that exceed the maximum 50 year return intervals as designated for NDT4 (e.g., plots 20, 27 and 34), and likewise have maximum return intervals that exceed or nearly exceed the minimum 100 year return intervals for NDT3 (e.g., plots 20, 34 and 39), a stand-replacing component to the fire history may not be entirely out of place. Furthermore, my sample design targeted fire-scarred trees that appeared to have the longest and most robust fire histories; within each search radii I avoided stands without fire-scar evidence in favor of those with evidence. As such, I cannot say that parts of the lower-elevation forests did not experience stand-replacing fires, as I did not test for this. Since the fire regime varies across space, this implies the observed CPFI may also be overestimating fire return intervals in the lower-elevations.

2.4.3.2 Recommendations for Improved NDT Schema

Due to the presence of fire scars providing evidence of low- to moderate-severity fires in all plots in the ICH zone in the study area, and because the present application of the British Columbia provincial NDT schema fails to capture observed variations in fire frequency and severity, I suggest the following changes for the classification of the forests in the southwestern part of the Darkwoods. Reclassify all ICH BEC units as NDT4 but maintain the ESSFdm subzone as NDT3. Application of this recommendation correctly classifies 22 of my research plots as having stand-maintaining fire regimes and correctly classified 16 plots as having stand-initiating fire regimes with a mean return interval of ca. 150 years (**Table 10**). Even with this proposed change, two plots in the ESSFdm subzone would remain misclassified as stand-replacing fires although fire scars were present. This discrepancy indicates that the current five-class NDT schema is incapable of capturing the full range of variation in fire severity that is endemic to the montane forests of southeastern British Columbia. Therefore, I recommend the NDT classification be modified to more accurately represent the variation of mixed-severity fire regimes that I have documented in the Darkwoods in southeastern B.C. Specifically, the ICHmw4 and ICHdw1 BEC variants should be reclassified as NDT4 and the descriptions of NDT4 and NDT3 should be modified to acknowledge the importance of mixed-severity fire regimes. Failure to recognize the limitations of the current NDT classification system has and will continue to provide misinformed guidance to forest managers in southeastern British Columbia, particularly in lower and mid-elevation forests where low- and mixed-severity fires evidently dominated historically, but current policies and management strategies assume that stand-replacing disturbances were dominant.

Chapter 3: Mapping Historical Fire Boundaries in Mixed-Severity Fire Regimes

3.1 Introduction

Forest and fire managers are increasingly mandated to conserve biodiversity and preserve ecosystem function while maintaining renewable resources in forested environments. Efforts are compounded by severe ecological disturbance events, particularly in light of a changing global climate, and as contemporary research unveils the degree to which forest structures have changed as a result of 20th century management policies. With fire as one of the most dangerous and contagious landscape disturbances, understanding the patterns of historical fires, both temporally and spatially, can better inform management strategies focused on shaping more resilient and fire-tolerant ecosystems. Reconstructing historical fires is the first step in achieving these goals.

3.1.1 Reconstructing Historical Fires From Fire-Scars

3.1.1.1 Fire Interval Statistics

Fire interval statistics are the traditional tools used to describe the temporal variability of surface fire regimes, as recorded by fire-scarred trees (Agee 1993, Baker and Ehle 2001, Kernan and Hessl 2010). The mean fire interval (MFI), a common measure of fire frequency, is used to quantify fire occurrence across a landscape (Kilgore and Taylor 1979, Agee 1993, Baker and Ehle 2001). MFI statistics benefit from the flexibility that they are able to describe fire occurrence at various scales.

At the individual tree-level, the smallest unit of measure in studies of fire history, the MFI is quantified by the mean point fire interval (MPFI) (Agee 1993, Heyerdahl 1997, Baker and Ehle 2001). The MPFI is calculated by averaging the time between fire events on fire-scarred trees. While fire scars provide affirmative evidence of the occurrence of fire at discrete point-locations, trees are not perfect recorders of fire (Swetnam *et al.* 2011). Fire scars may fail to form if cambial cell damage does not occur, or may be erased from the record by subsequent fires, mechanical damage, or rot (Van Pelt and Swetnam 1990, Parsons *et al.* 2007, Swetnam *et al.* 2011). The MPFI, therefore, is subject to false negatives, causing potential overestimation of fire intervals (Kilgore and Taylor 1979, Fall 1998, Baker and Ehle 2001).

This issue can be offset by incorporating MPFI data into composite mean fire interval (CMFI) records at broader scales (Dieterich 1980, Parsons *et al.* 2007). The CMFI is typically generated at the study site-, or plot-level, representing intermediate-scale assessments, but may also be generated across a watershed, representing large-scale assessments. Compositing increases the likelihood of obtaining complete inventories of major fires (Farris *et al.* 2010), but homogenizes the fire interval within the study area, preventing finer grain analyses (Kernan and Hessl 2010).

Kernan and Hessl (2010) introduced the spatial mean fire interval (SMFI) as a technique for investigating spatio-temporal variability in fire, using a geographic information system (GIS). An SMFI is a spatially explicit method for calculating and representing MFI, and is constructed by interpolating between fire scar point data. Though an SMFI cannot address false negatives associated with MPFI, it may compensate for the potential loss of fire scar evidence by estimating burn perimeters in unsampled areas between fire-scarred trees

(Kernan and Hessl 2010). Furthermore, compared to CMFI, an SMFI can enable finer grain analyses of the causes and effects of fire within study areas (Kernan and Hessl 2010).

3.1.1.2 Mapping Fire Boundaries

While fire interval statistics provide insight to the temporal variability of historical fire regimes, mapping the impact and extent of historical fires on the surrounding landscape allows for analysis of their spatial patterns (Hessl et al. 2007, Swetnam et al. 2011). Maps present information that is both visual and quantifiable, including the heterogeneity inherent to fire – conveyed as patchy mosaics of burn patterns across the landscape, and estimates of fire perimeters, including area burned. Such information can bolster forest and fire management decisions that are based primarily on temporal analyses.

Hessl et al. (2007) described and compared several techniques for mapping historical fire boundaries. The most common approach, the "expert" approach, requires fire behaviour experts to draw fire boundaries by hand based on point locations of fire-scarred trees, relative to their topographic situation and surrounding fuel loads (Hessl *et al.* 2007). This method provides ecologically meaningful results, but is time consuming and subject to human bias due to differing interpretations of fire behaviour among experts (Hessl *et al.* 2007).

Hessl *et al.* (2007) also assessed three less-subjective, computer-based techniques for mapping historical fire boundaries from point data: Thiessen polygons (TP), indicator kriging (IK), and inverse distance weighting (IDW). Though the simplest to parameterize and the least computationally intensive, the TP method produced results that were not ecologically meaningful in broad-scale studies, as fire burn shapes were unrealistic, preventing additional analysis on spatial pattern. The IK method produced ecologically meaningful results, but suffered from a high degree of subjectivity in model parameterization, and was computationally intensive. IDW was found to produce the best overall results, requiring some subjective parameterization, but was otherwise the most efficient, ecologically interpretable, and relatively accurate method for reconstructing spatial patterns of historical fires. (For complete descriptions of these methods, see Hessl et al. 2007 and Swetnam et al. 2011.)

3.1.2 Using Tree (Cohort) Ages to Reconstruct Historical Fires

In areas subject to mixed- and high-severity fire regimes, fire scar evidence may be uncommon or missing entirely. This is particularly problematic in mid- and high-elevation forests dominated by thin-barked, shade-tolerant tree species that are highly intolerant of fire (Agee 1993). In these forests, indirect evidence of fire is collected by extracting cores from cohorts of trees that are assumed to have established after the last stand-replacing fire (Johnson and Fryer 1989, Johnson et al. 1994, Antos and Parish 2002). Tree cores are used to determine stand age and, by extension, the approximate year of the last fire. In areas dominated by mixed-severity fires, or adjacent to areas dominated by high-severity fires, cohort ages can be compared to fire years from scars on neighbouring trees, allowing for potential verification of the year of the last stand-replacing fire (Kipfmueller and Baker 2000, Sibold et al. 2006). In this sense, cohorts of fire-intolerant species provide indirect evidence of fire by serving as proxies for the absence of fire throughout the lifetime of each tree.

3.1.3 Objective

In this paper, I describe methods for reconstructing historic fire boundaries and generating SMFI's using a GIS and fire history data collected in and around areas dominated by mixed- and high-severity fire regimes. This study differs from previous studies in that it includes tree cohort data taken from sites without direct evidence of fire. I am interested in assessing the degree to which fire boundary and SMFI estimations change when tree cohort data is included in analyses. Due to the loss of the fire record by subsequent high-intensity fires, particularly in mixed-severity fire regimes, reconstructed fire boundaries may not reflect accurate sizes of fire events. Therefore, I am also interested in mapping fine-scale boundaries for fires of all sizes, as even the smallest fires may have had a larger impact on the landscape than the fire-scar record indicates.

To assess the affect of including tree cores in reconstructions of historic fire boundaries and in generating SMFI surfaces, I perform sensitivity analyses to assess (1) the overall impact on model estimation, (2) how parameterization of the model changes, and (3) how the SMFI relates to MPFI and CMFI. Parameterization affects the extent to which interpolations are made, therefore affecting the estimated fire boundaries. I conclude with suggestions for optimal model performance for similar studies taking place in and around mixed- and high-severity fires.

3.2 Methods

3.2.1 Study Area

The study site is a 3,870-ha portion of the southeastern-most watershed of the Darkwoods, a 55,000-ha property owned and managed by the Nature Conservancy of Canada. Located on the leeward side of the Selkirk Range, on the western side of the Creston Valley (49˚ 12' N, 116˚ 41' W; mean elevation 1,670 m) **(Figure 3.1)**, the study site is generally east-facing, with terrain varying from barren, rocky peaks and gentle, moderate slopes in the high elevations (maximum elevation 2,875 m), to steep drainages and exposed rocky outcrops in the lower elevations (valley bottom 468 m). From valley bottom to altitudinal tree-line, vegetation is a complex mix of conifers. The lower elevations are dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) in the warmer and more complex terrain (e.g., rocky outcrops), and by western redcedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) in the cooler, more mesic areas (e.g., along drainages). Mid-elevations are co-dominated by western larch (*Laryx occidentalis*) and Douglas-fir in the warmer aspects, and western redcedar and western hemlock in the cooler aspects. The highest elevations are co-dominated by Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), with isolated stands of western larch. Lodgepole pine (*Pinus contorta*) is subdominant across the mid- and high-elevations.

Darkwoods is located in the traditional territory of the Ktunaxa Nation. The Ktunaxa people have occupied the lands adjacent to the Kootenay and Columbia Rivers and the Arrow Lakes of British Columbia for approximately 4,000 - 10,000 years (Ktunaxa Nation 2005). Fire was an integral part of Ktunaxa use of the landscape, as documented through verbal history (Cochrane 2007).

Beginning in the 1830s, Euro-American homesteads appeared throughout the Columbia Basin, an area quite isolated until this time (Ktunaxa Nation 2005). In the 1850s, the first Euro-American settlers arrived on the Darkwoods property (The Nature Conservancy of Canada 2008). Henceforth, land-use practices changed from those established by the Ktunaxa people, of which vegetation and forest structures mirrored and were well-adapted for at least the last 4,000 years, to those focused on maximizing opportunities for mining, logging and ranching purposes. In 1912 the Wildfire Management Branch, the first forest fire fighting agency British Columbia, was formed (BC Ministry of Forests and Range 2011). Modern methods of fire suppression evolved in the 1940s through the advent of smoke jumpers and aerial tanker suppression (Agee 1993). These land-use and fire exclusion practices are known to have altered existing forest structures and greatly reduced the occurrence of less-severe fires across the western United States (Agee 1993, Brown *et al.* 1999, Fule *et al.* 1997, Taylor 2000, Veblen *et al.* 2000,) and in southeastern British Columbia (Cochrane 2007, Da Silva 2009, Nesbitt 2010).

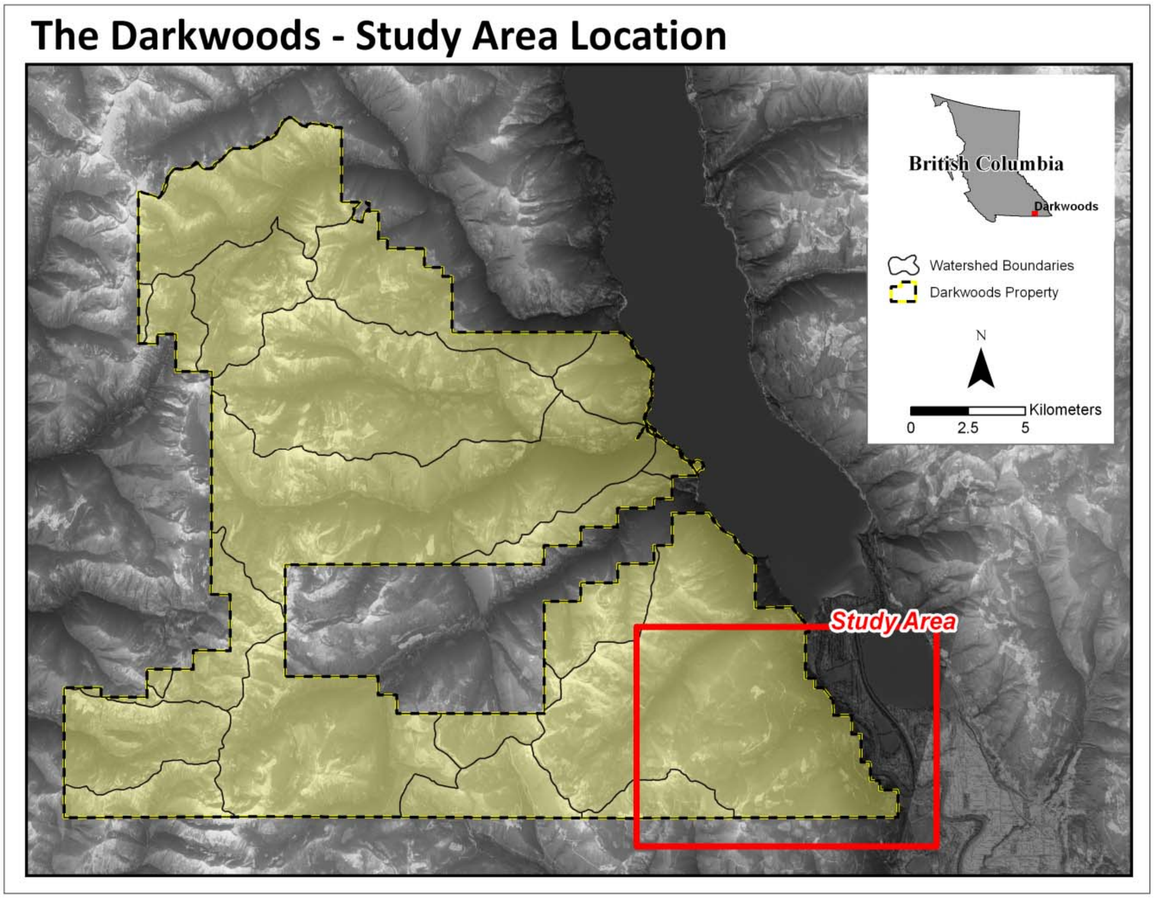

Figure 3.1 The study area, located in the southeast watershed of the NCC's "Darkwoods" property.

3.2.2 Research Design and Data

3.2.2.1 Systematic Sample Design

To establish the site's fire history, I targeted samples within a gridded, systematic sampling design. A GIS was used to randomly place a 1 km x 1 km systematic grid within the study site, spanning 11 km east to west, and 8 km north to south **(Figure 3.2)**. A 500 m radius surrounding each grid intersection point was searched for evidence of fire, and a plot was placed around targeted trees with the most scar lobes that appeared to provide the longest and most robust fire history. In total, I established forty 1-ha fixed area research plots **(Figure 3.2)**. Five additional "supplemental" plots were established at intermediate points within the grid to enhance the resolution of the fire boundary reconstructions **(Figure 3.2)**. Plot configurations were either circular (n = 42, r = 56.4 m) or rectangular (n = 3, dimensions = 250 x 40 m, 200 x 50 m, and 150 x 66 m), and plot reference points (plot centre in circular plots and plot corner in rectangular plots) were recorded with a GPS. The distance and bearing of sampled tree locations were measured from their respective plot reference points using a laser range-finder and compass, the results of which were used to reconstruct tree locations in a GIS. Furthermore, slope aspect and slope steepness were measured for each plot using a compass and inclinometer. The presence/absence of charcoal on each tree and surrounding soil, and the morphology of each scar (e.g., scar open/closed, scar reaches base of tree), if present, were also documented as corroborative evidence for the occurrence of fire.

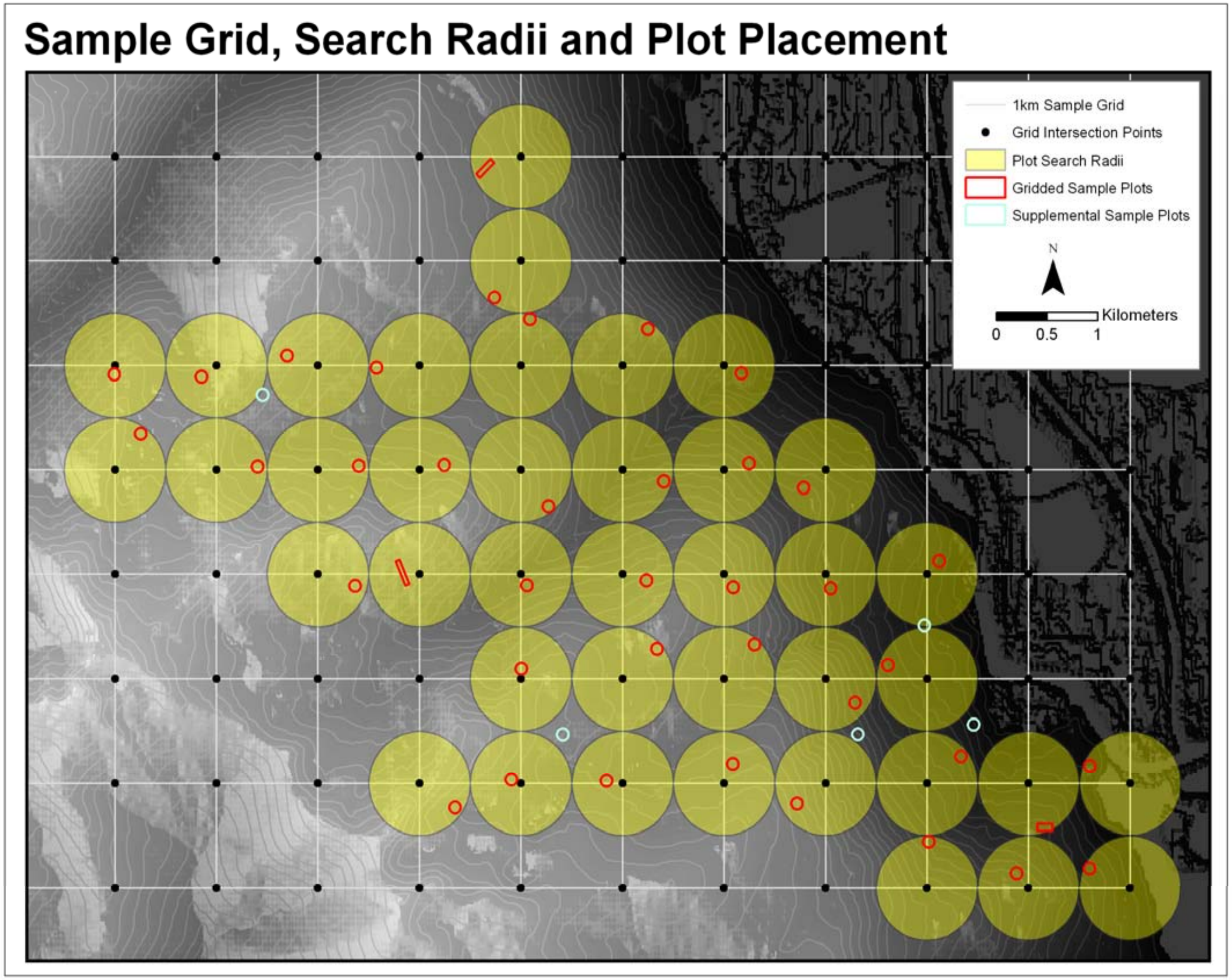

Figure 3.2 Sample grid, 500 m search radii, and plot locations in the 11 x 8 km study area.

3.2.2.2 Sample Extraction and Preparation

No fire scar evidence was apparent in 15 of the 45 plots. At these points, I cored 10 canopy trees to approximate stand age and to represent the fire-free period at these sites. Fire scar evidence was present in the remaining 30 plots. Within each of these plots, full and partial cross sections were cut from up to seven snags, stumps, logs and/or live trees with the greatest number of visible scars (μ = 4.5 trees plot^{-1}). One plot, located in the higher elevations, yielded only one fire scar sample, so 10 additional canopy-dominant trees were cored to determine stand age. In total, 291 trees were sampled (μ = 6.3 trees plot^{-1}, mean sample density = 0.074 trees ha^{-1}), including 160 cores and 131 fire scar cross sections.

Samples were sanded until the cell structure was visible with a binocular microscope, and calendar years were assigned to tree rings using a combination of visual cross-dating of ring widths and cross-correlation of measured ring-width series (Holmes, 1983; Grissino-Mayer, 2001a). I could not cross-date 3.4% (n=10: 6 cores, 4 cross sections) of the sampled trees due to excessive rot or complacency in ring growth, so they were excluded them from further analysis. One additional cross-section was dated outside the period of analysis, so was also excluded. Therefore, a total of 285 samples were used in this study.

3.2.3 GIS Methods and Analysis

For spatial reconstruction, the period between 1700 and 1945 was analyzed, as ~25% of plots (n = 11) had a record of fire by 1700, and the occurrence of fires is known to have decreased dramatically after modern methods of fire suppression were introduced in British Columbia the 1940s (Cochrane 2007, Da Silva 2009, Nesbitt 2010). Fire events that scarred less than two trees were excluded from analysis to eliminate possible non-fire injuries. In total, 20 fire years, recorded by 294 scars, were assessed during this period.

3.2.3.1 Recreating Historical Fire Boundaries

Inverse distance weighting (IDW) algorithms were used to interpolate fire occurrence over the landscape between sampled points (Hessl *et al.* 2007, Kernan and Hessl 2010, Swetnam *et al.* 2011), generating burn likelihood surface maps for each fire year. To estimate fire boundaries, threshold values were calculated and applied as minimum likelihood selection criteria. Likelihood values exceeding these threshold values were interpreted as areas that burned (fire = 1), while those less than the threshold values were interpreted as unburned areas (fire = 0). The "line" dividing these two areas was interpreted as the fire perimeter. Analyses were conducted at both the tree- and plot-level. Therefore, IDW interpolations were based on separate binary *year x fire* matrices (fire = 1, no fire = 0), compiled using individual tree-level and composited plot-level fire records (Swetnam *et al.* 2011). Study area boundaries, used to "clip" all subsequent GIS outputs, were defined using convex hulls (Hessl *et al.* 2007, Kernan and Hessl 2010). Depending on the analysis at hand, convex hulls were constructed around either the sampled trees or plot reference points. Mean Euclidean nearest-neighbour distances (μ_{NN}) between trees were calculated and applied as buffers on the convex hulls in all tree- and plot-level analyses (Hessl *et al.* 2007, Kernan and Hessl 2010).

3.2.3.2 Spatial Estimates of Fire Frequency

I generated SMFIs at both tree- and plot-levels using a modified approach based on Kernan and Hessl (2010). Convex hulls, buffered using the mean nearest-neighbour distance (μ_{NN}) between trees, were applied as site boundaries and used to clip all subsequent GIS outputs. I did not generate study area boundaries by buffering each set of points by the minimum distance necessary to create a single polygon, per Hessl *et al.* (2007) and Kernan and Hessl (2010), because attempts to use these or similar boundaries (e.g., using the sample grid as a boundary) resulted in extensive overlap of surrounding features that act as barriers to fire spread (e.g., barren, rocky peaks in the high elevations, and a river at eastern edge of the study area). Potentially, GIS can be used to "erase" these overlapping features from the boundary, but this method, and its potential effect on modelling results, was not explored in this study.

3.2.3.3 Investigation I: The Effect of Cored Trees on Fire Boundary Estimations

To assess the effect of including ring-width series from cored trees in estimated fire boundaries, sensitivity analysis was used to compare the results of two different datasets. First, fire likelihood surfaces were calculated using only fire scar samples ("traditional" dataset, n = 129 trees, μ_{NN} = 31.4 m). Second, fire likelihood surfaces were calculated using all samples, including fire scars and cores ("modified" dataset, n = 285 trees, μ_{NN} = 17.0 m). As the modified dataset encompasses a larger area than the traditional dataset, comparisons were made between the overlapping portions of the two datasets **(Figure 3.3).** Following Hessl et al. (2007) and Kernan and Hessl (2010), all likelihood surfaces were interpolated using the 12 nearest neighbours and generated at a resolution of 50 m. Fire perimeters and

SMFI surfaces were estimated using the "traditional" and "modified" datasets, and differences in area burned (total, mean, min and max) and SMFI estimations were assessed between the overlapping areas. To eliminate bias in area burned estimations, all fire perimeters were calculated by selecting burn likelihood cells that exceeded a fixed threshold value of 0.5.

3.2.3.4 Investigation II: Assessing Threshold Estimations Given Cored Trees

To determine the sensitivity to different fire boundary thresholds, given the additional cored trees, three parallel analyses were conducted. First, the ratio of fire-scarred trees that recorded a scar during each event relative to the total number of potential recorder (living, previously fire-scarred) trees was calculated for each fire year. Fire perimeters were generated by selecting cells that exceeded a threshold equal to the ratio calculated for each fire year (“liberal” threshold; Hessl *et al.* 2007; Kernan and Hessl 2010). Second, fire perimeters were generated using a threshold equal to the ratio of fire-scarred trees that recorded a scar during each event relative to the total number of living trees. In this calculation, the living trees included cored trees and all fire-scarred trees that were alive during the year of the fire (“conservative” threshold). By including all cored trees as potential recorders, threshold values are expected to either stay the same or decrease in value compared to "liberal" thresholds, thus generating smaller overall fire perimeters. Third, fire perimeters were generated based on a fixed threshold of 0.5 (“fixed” threshold). The number of polygons generated, area burned (total, mean, min and max) and SMFI estimations were calculated for each analysis, the results of which were compared.

I am also interested in identifying whether threshold analyses over or under-estimated area burned. Estimated area burned is directly related to the number and location of scarred trees and neighbouring recorders. Therefore, departures from a 1:1 relationship would indicate spatial burn patterns that are not random or uniform (Hessl et al. 2007). To assess the degree of departure from a linear relationship with percentage scarred, I visually compared the estimated percentage of the study area burned generated by each threshold analyses to the percentage of recorders scarred, a commonly used index of fire extent (Morrison and Swanson 1990, Swetnam and Betancourt 1990, Fule and Covington 1999, Veblen et al. 1999; Niklasson and Granström 2000, Taylor and Skinner 2003, Hessl et al. 2007).

3.2.3.5 Investigation III: SMFI vs. MPFI and CMFI

Descriptive statistics (mean and standard deviation) were calculated for each SMFI map and compared with results from the point data for the MPFI and the CMFI, both statistical measures of fire frequency (Chapter 2).

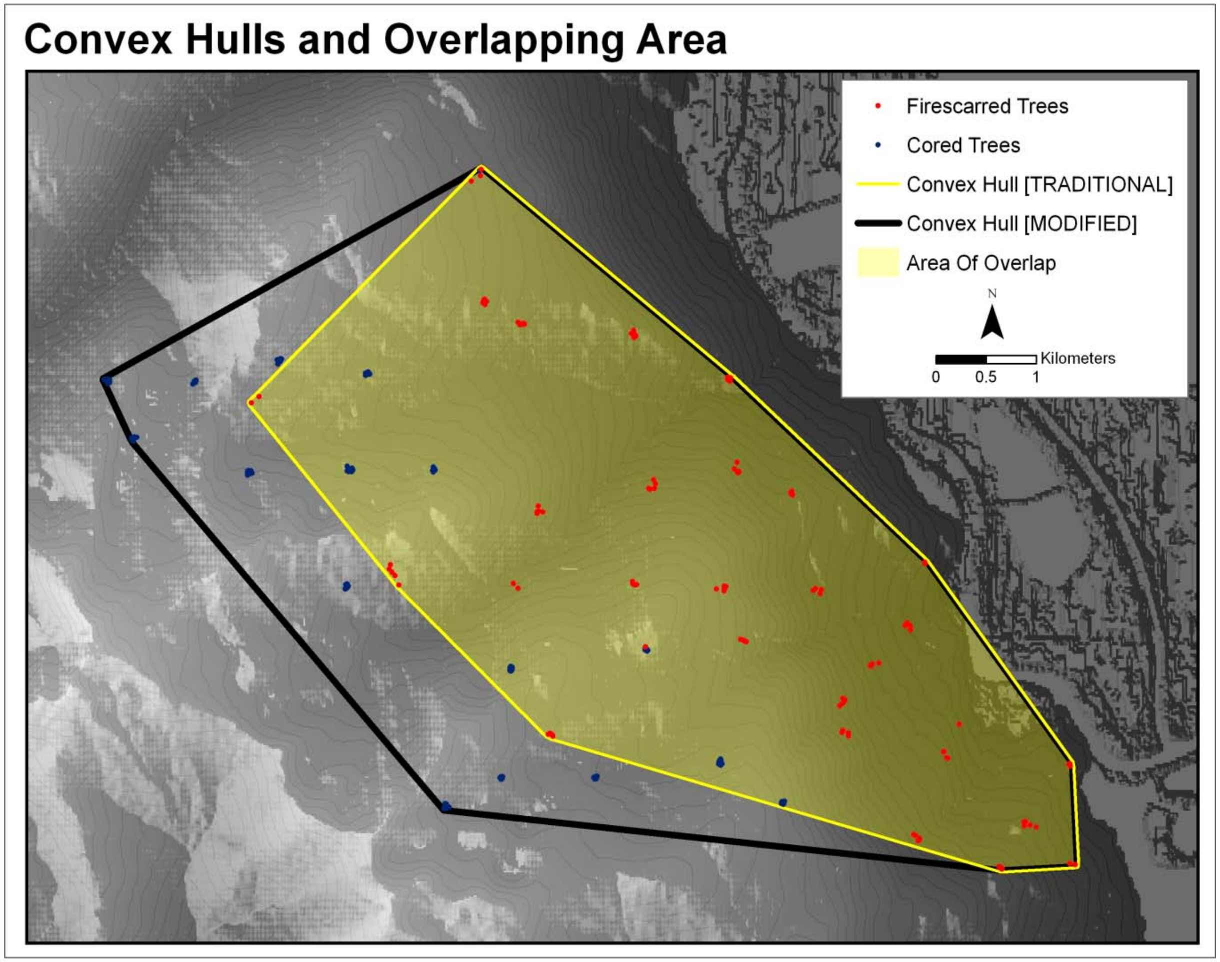

Figure 3.3 Tree-level convex hulls generated using the "traditional" dataset (yellow outline), the "modified" dataset (black outline), and the resulting area of overlap (yellow shaded area).

3.3 Results

3.3.1 Investigation I: The Effect of Cored Trees on Fire Boundary Estimations

3.3.1.1 Tree-Level

Convex hulls generated at the tree-level encompassed slightly larger areas than those at the plot-level **(Table 3.1)**. Area burned estimates derived from the tree-level fire-occurrence data indicated large differences between the "traditional" and "modified" datasets. Calculations based on the traditional dataset estimated a total of 9,294.4 ha burned by the 20 fires (average area burned per fire = 211.2 ha). The modified dataset produced an estimate of 8,432.4 ha (average area burned per fire = 191.7 ha), a reduction of 862.0 ha in total area burned and 19.5 ha in average area burned per fire **(Table 3.2)**. Spatial mean fire intervals did not differ between the overlapping portion of the two datasets (SMFI = 59.8 yr) **(Table 3.2)**.

Table 3.1 Area, mean nearest-neighbour (μ_{NN}) distance, sample size (number of plots and trees), number of scars, and number of fire events for each bounding convex hull. Fire events were included if they scarred two or more trees during the period of analysis, 1700 - 1945. The convex hull boundary without cores includes only fire scar samples, while the convex hull boundary with cores includes sampled trees in plots where no fire scar evidence was present.

Dataset	Convex Hull Area (ha)		μ_{NN} (m)	Plots	Trees	Scars	Fire Events
	Tree-Level	Plot-Level					
TRADITIONAL	2,718	2,687	31.4	30	129	294	20
MODIFIED	3,671	3,632	17	45	285		

3.3.1.2 Plot-Level

In general, area burned estimates are larger for the plot-level analysis than for the tree-level analysis, though differences between the overlapping portions of the traditional dataset and the modified dataset were not as large. Calculations based on the traditional dataset estimated a total of 10,312.6 ha burned (average area burned per fire = 332.7 ha), while the overlapping portion of the modified dataset estimated 9,742.9 ha burned (average area burned in each fire = 314.3 ha), a reduction of 569.7 ha in total area burned and an average reduction of 18.4 ha per fire **(Table 3.2)**. Spatial mean fire intervals at the plot-level did not differ greatly, with the overlapping portion of the modified dataset estimating a 1.7 year reduction in mean return interval compared to traditional dataset estimates **(Table 3.2)**.

Table 3.2 Tree-level area burned estimates for all fires occurring between 1700 and 1945. The MODIFIED dataset includes all cored and fire-scarred trees, while the TRADITIONAL dataset only includes fire-scarred trees. Statistics include the number of recorders, total and mean estimated area burned and standard deviation (SD), spatial mean fire interval (SMFI) and standard deviation (SD) derived from GIS.

Analysis Level	Dataset	Recorders	Area Burned (ha)			SMFI	SD
			Total	Mean	SD		
Trees	MODIFIED	3,581	9,297.3	211.3 (0.17, 2126)	433.4	59.8 (17, 151)	34.9
	MODIFIED [Overlapping Portion]	-	8,432.4	191.7 (0.17, 1500)	467.7	59.8 (17, 151)	34.9
	TRADITIONAL	1,661	9,294.4	211.2 (0.17, 1568)	404.5	59.8 (17, 151)	34.5
Plots	MODIFIED	716	10,921.7	352.3 (11, 2637)	576.1	52.4 (25, 136)	27.2
	MODIFIED [Overlapping Portion]	-	9,742.9	314.3 (11, 1846)	467.7	52.4 (25, 136)	27.2
	TRADITIONAL	505	10,312.6	332.7 (12, 1848)	479.8	54.1 (25, 136)	27.8

3.3.2 Investigation II: Assessing Threshold Estimations Given Cored Trees

3.3.2.1 Tree-Level

At the tree-level, fixed thresholds generated estimates for all fire years, but conservative and liberal thresholds did not produce estimates for three of the fires years (1895, 1909 and 1926) **(Table 3.3)**. Conservative thresholds resulted in the greatest number of polygons generated (n = 60), the least area burned (total = 4,396.6 ha, mean = 74.5 ha, median = 66 ha), and the shortest return intervals (56 yr, n = 32 intervals) **(Table 3.4)**. Liberal thresholds resulted in the opposite effect, generating the fewest number of burn polygons (n = 43), a greater area burned (total = 7,648.12 ha, mean = 177.9 ha, median = 110 ha), and the longest return interval (62 yr, n = 27 intervals). Overall, fixed thresholds estimated the greatest area burned (9,297.3 ha, mean = 211 ha, median = 171 ha), but otherwise produced a similar number of polygons to the liberal calculations (n = 44), and mean return intervals between those of the conservative and liberal estimates (60 yr, n = 39 intervals). All three thresholds resulted in the same minimum area burned estimation (0.17 ha burned in one fire polygon), though liberal thresholds produced the largest individual burn estimate (2,147 ha burned in one fire polygon).

The percentage scarred increased at a faster rate than area burned for all thresholds, indicating percentage area burned was consistently underestimated **(Figure 3.4)**. Furthermore, the two right-most data points in each graph, representing the largest, most wide-spread fires, caused an overall negative trend in the data. These two extreme data points are the 1823 and 1869 fires in the conservative threshold estimates, and the 1739 and 1869 fires in the liberal and fixed estimates. In general, fixed thresholds better estimated smaller fires than either conservative or liberal estimates, noted by a smaller y-intercept value.

Table 3.3 Tree-level threshold analysis results for each fire year, including number of scars, the threshold calculation (Thresh), number of burn polygons generated (Poly) and total area burned. The highlighted values are years when fire boundaries were not generated by conservative and liberal thresholds.

		Conservative				Liberal				Fixed		
Year	Scars	Prcnt Record	Thresh	Poly	Area Burned (ha)	Prcnt Record	Thresh	Poly	Area Burned (ha)	Thresh	Poly	Area Burned (ha)
1718	4	22.46	0.063	2	17.88	13.95	0.222	1	91.34	0.500	2	395.26
1739	13	24.21	0.188	7	502.76	18.60	0.542	3	1464.67		3	1351.20
1768	13	32.28	0.141	1	294.60	24.03	0.419	3	713.37		1	910.26
1795	12	38.95	0.108	3	292.31	31.78	0.293	2	543.89		4	762.40
1823	34	44.21	0.270	1	868.96	48.06	0.548	1	1048.25		1	1004.26
1831	20	46.67	0.150	6	176.39	57.36	0.270	5	277.21		5	480.76
1843	6	50.18	0.042	1	9.56	59.69	0.078	1	18.99		2	190.86
1847	2	50.88	0.014	1	0.17	60.47	0.026	1	0.17		1	37.80
1848	3	51.23	0.021	1	0.17	62.02	0.038	1	0.17		2	11.58
1866	13	51.93	0.088	1	95.18	63.57	0.159	1	109.75		1	151.16
1869	49	52.28	0.329	5	1775.09	73.64	0.516	4	2198.89		3	2169.23
1879	6	68.42	0.031	1	1.58	74.42	0.063	1	3.58		2	34.71
1886	45	85.96	0.184	14	238.37	83.72	0.417	6	743.13		2	912.36
1889	19	88.77	0.075	2	65.98	86.05	0.171	3	84.77		1	148.70
1895	**3**	**91.23**	**0.012**	-	-	**83.72**	**0.028**	-	-		1	4.35
1904	36	92.28	0.137	11	55.16	90.70	0.308	8	344.38		7	584.80
1909	**3**	**91.58**	**0.011**	-	-	**89.92**	**0.026**	-	-		2	0.34
1920	5	91.23	0.019	1	0.17	89.15	0.043	1	0.17		2	58.98
1924	5	90.88	0.019	1	2.24	88.37	0.044	1	5.42		1	65.98
1926	**3**	**90.88**	**0.012**	-	-	**88.37**	**0.026**	-	-		1	22.30
				Mean:	*74.52*				*177.86*			*211.30*
				Median:	*65.98*				*109.75*			*171.01*
				SD:	*454.06*				*623.44*			*575.00*
				Sum:	*4,396.57*				*7,648.15*			*9,297.28*

Table 3.4 Area burned and fire interval statistics for the three threshold classes, at both the tree- and plot-levels. Results are for the 20 fire events that occurred between 1700 and 1945 that scarred two or more trees. Area burned statistics include the number of polygons generated in the GIS (Poly), the total area burned (Total), and the average area burned (Mean) and standard deviation (SD). Fire interval statistics include the number of intervals generated in the GIS (Intervals), spatial mean fire interval (SMFI) and standard deviation (SD) derived from the GIS. Minimum and maximum values are shown in parenthesis for mean area burned and SMFI.

Analysis Level	Threshold	Area Burned				Fire Intervals		
		Poly	Total (ha)	Mean (ha)	SD	Intervals	SMFI	SD
Trees	Conservative	60	4,396.6	74.5 (0.17, 1735)	254.1	32	55.7 (8, 147)	30.4
	Liberal	43	7,648.1	177.9 (0.17, 2147)	423.6	27	62.1 (17, 147)	32.6
	Fixed	44	9,297.3	211.3 (0.17, 2126)	433.4	39	59.8 (17, 151)	34.9
Plots	Conservative	42	7,635.9	181.8 (0.34, 2613)	472.2	32	64.4 (29, 165)	36.1
	Liberal	33	9,524.7	288.6 (0.34, 2712)	607.3	31	57.3 (25, 136)	28.2
	Fixed	31	10,921.7	352.3 (11.4, 2637)	576.1	33	52.4 (25, 136)	27.2

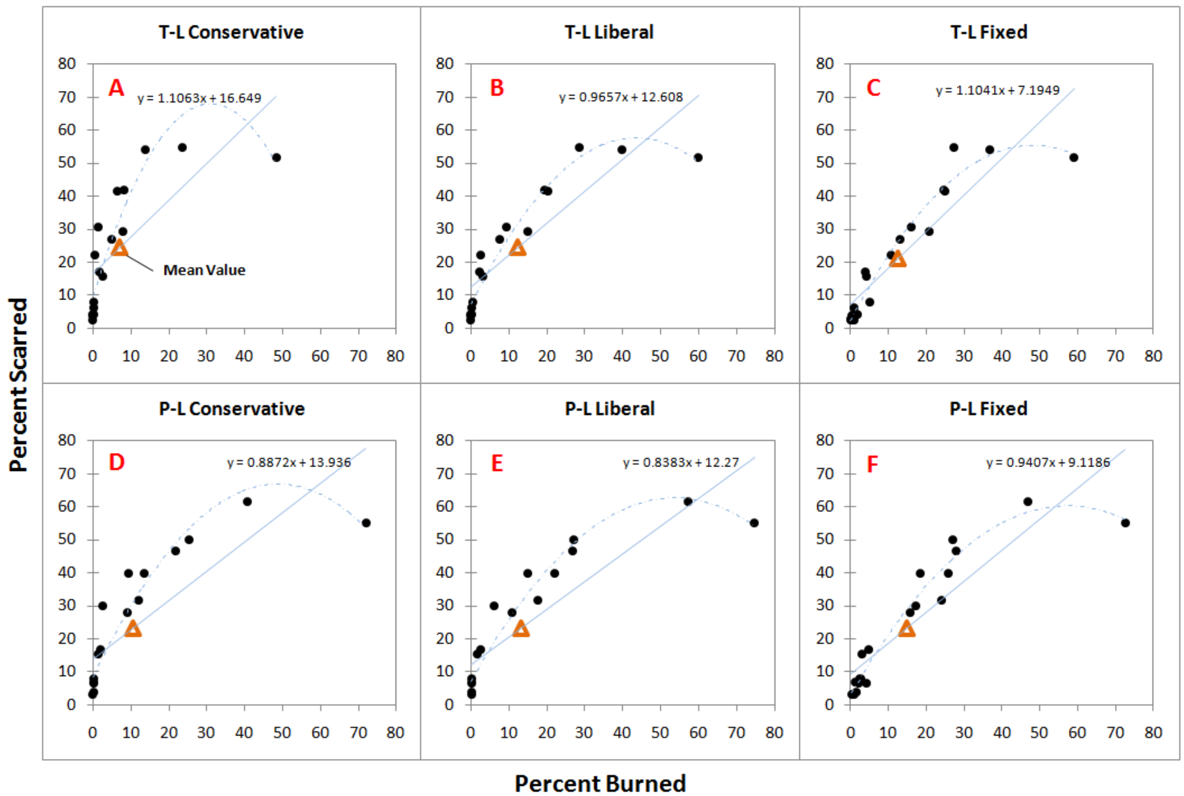

Figure 3.4 Percent scarred versus estimated percentage of study area burned for (A) tree-level conservative thresholds, (B) tree-level liberal thresholds, (C) the tree-level fixed thresholds, (D) plot-level conservative thresholds, (D) plot-level liberal thresholds, and (F) plot-level fixed thresholds. The solid lines and equations represent the linear averages, while the dashed lines represent the general trending of the data.

3.3.2.2 Plot-Level

Area burned estimates were generated for all fire years in all threshold analyses at the plot-level **(Table 3.5)**. Fixed threshold calculations resulted in the least number of burn polygons (n = 31), the greatest total area burned (10,921.7 ha, mean = 352 ha, median = 166 ha), and the shortest spatial mean return interval (52 yr, n = 33 intervals), while conservative thresholds produced the greatest number of polygons (n = 42), the least total area burned (7,635.9 ha, mean = 182 ha, median = 62 ha), and the longest return interval (64 yr, n = 32 intervals) **(Table 3.4)**. Liberal estimates were intermediate with 33 polygons, a total of 9,524.7 ha burned (mean = 289 ha, median = 78 ha), and a return interval of 57 yr (n = 31 intervals). All three thresholds resulted in similar maximum area burned polygons (between 2,613 and 2,712 ha). However, the smallest fire polygon generated by the fixed thresholds was 11.4 ha; 11.1 ha more than the minimum burn polygons generated by either the conservative or liberal thresholds (minimum = 0.34 ha for both).

As with the tree-level analysis, conservative, liberal and fixed threshold percentage burned estimates were consistently underestimated at the plot-level, and the data exhibited a generally negative trend, being biased by the two largest and most widespread fires in 1739 and 1869 (the most extreme right data points in all plots; **Figure 3.4).** Likewise, fixed thresholds better estimated smaller fires than either conservative or liberal estimates, as noted by a smaller y-intercept value. Overall, plot-level estimates were improvements over their tree-level counterparts.

Table 3.5 Plot-level threshold analysis results for each fire year, including number of scars, percent of potential recorders relative to the total number of recorders (Prcnt Record), the threshold calculation (Thresh), number of burn polygons generated (Poly) and total area burned.

		Conservative				Liberal				Fixed		
Year	Scars	Prcnt Record	Thresh	Poly	Area Burned (ha)	Prcnt Record	Thresh	Poly	Area Burned (ha)	Thresh	Poly	Area Burned (ha)
1718	3	6.99	0.150	2	87.73	7.75	0.300	2	224.93	0.500	2	630.68
1739	8	7.34	0.381	2	1482.36	10.08	0.615	1	2074.16		2	1703.15
1768	6	9.44	0.222	2	485.91	11.63	0.400	1	799.33		1	942.96
1795	6	10.14	0.207	2	439.25	14.73	0.316	2	634.05		1	878.88
1823	12	10.49	0.400	1	914.73	18.60	0.500	1	985.34		1	985.34
1831	7	11.19	0.219	2	330.64	19.38	0.280	2	388.98		2	577.03
1843	2	11.19	0.063	2	7.49	19.38	0.080	2	8.31		2	96.99
1847	1	11.19	0.031	1	2.87	19.38	0.040	1	3.12		1	55.98
1848	2	11.54	0.061	2	6.48	19.38	0.080	2	8.86		2	88.14
1866	4	11.54	0.121	2	52.29	20.16	0.154	1	63.29		1	114.60
1869	16	11.54	0.485	1	2613.09	22.48	0.552	1	2712.40		1	2637.15
1879	2	14.69	0.048	2	2.18	22.48	0.069	2	3.75		2	43.41
1886	14	15.38	0.318	3	792.28	23.26	0.467	2	971.25		2	1015.66
1889	5	15.38	0.114	2	72.30	23.26	0.167	2	92.05		1	177.14
1895	1	15.38	0.023	1	0.34	23.26	0.033	1	0.34		1	11.41
1904	12	15.38	0.273	9	335.85	23.26	0.400	4	537.97		4	671.26
1909	2	15.38	0.045	2	3.01	23.26	0.067	2	5.20		2	81.60
1920	2	15.38	0.045	2	5.43	23.26	0.067	2	9.43		1	153.82
1924	1	15.38	0.023	1	0.67	23.26	0.033	1	0.67		1	32.49
1926	1	15.38	0.023	1	0.95	23.26	0.033	1	1.26		1	23.97
				Mean:	*181.81*				*288.63*			*352.31*
				Median:	*62.30*				*77.67*			*165.48*
				SD:	*658.62*				*746.31*			*681.92*
				Sum:	*7,635.87*				*9,524.71*			*10,921.68*

3.3.3 Investigation III: SMFI vs. MPFI and CMFI

SMFI was longer than MPFI and CMFI for all thresholds in both tree- and plot-level analyses. At the tree-level, conservative estimates yielded the shortest return intervals (55.7 yr) while liberal estimates yielded the longest intervals (62.1 yr). Fixed thresholds produced return intervals intermediate to conservative and liberal estimates (59.8 yr) **(Table 3.6)**. Conversely, conservative estimates at the plot-level yielded the longest intervals (64.4 yr), fixed estimates yielded the shortest intervals (52.4 yr), and liberal thresholds produced return intervals intermediate to conservative and fixed estimates (57.3 yr) **(Table 3.6, Figure 3.5)**.

Table 3.6 Fire interval statistics for the each threshold class, at both the tree- and plot-levels, compared to traditional point data statistics. Results are for the 20 fire events that occurred between 1700 and 1945 that scarred two or more trees. Statistics include the spatial mean fire interval (SMFI) and standard deviation (SD) derived from the GIS, mean point fire interval (MPFI) and standard deviation (SD), and Composite Mean Fire Interval (CMFI) and standard deviation (SD). MPFI is based on point data from individual trees, and CMFI is based on composites of all trees for each plot. Minimum and maximum values are shown in parenthesis for SMFI, MPFI and CMFI.

Analysis Level	Threshold	SMFI	SD	Point-Based Fire Intervals			
				MPFI	SD	CMFI	SD
Trees	Conservative	55.7 (8, 147)	30.4	40.4 (6, 147)	25.6	37.8 (3, 136)	13.1
	Liberal	62.1 (17, 147)	32.6				
	Fixed	59.8 (17, 151)	34.9				
Plots	Conservative	64.4 (29, 165)	36.1				
	Liberal	57.3 (25, 136)	28.2				
	Fixed	52.4 (25, 136)	27.2				

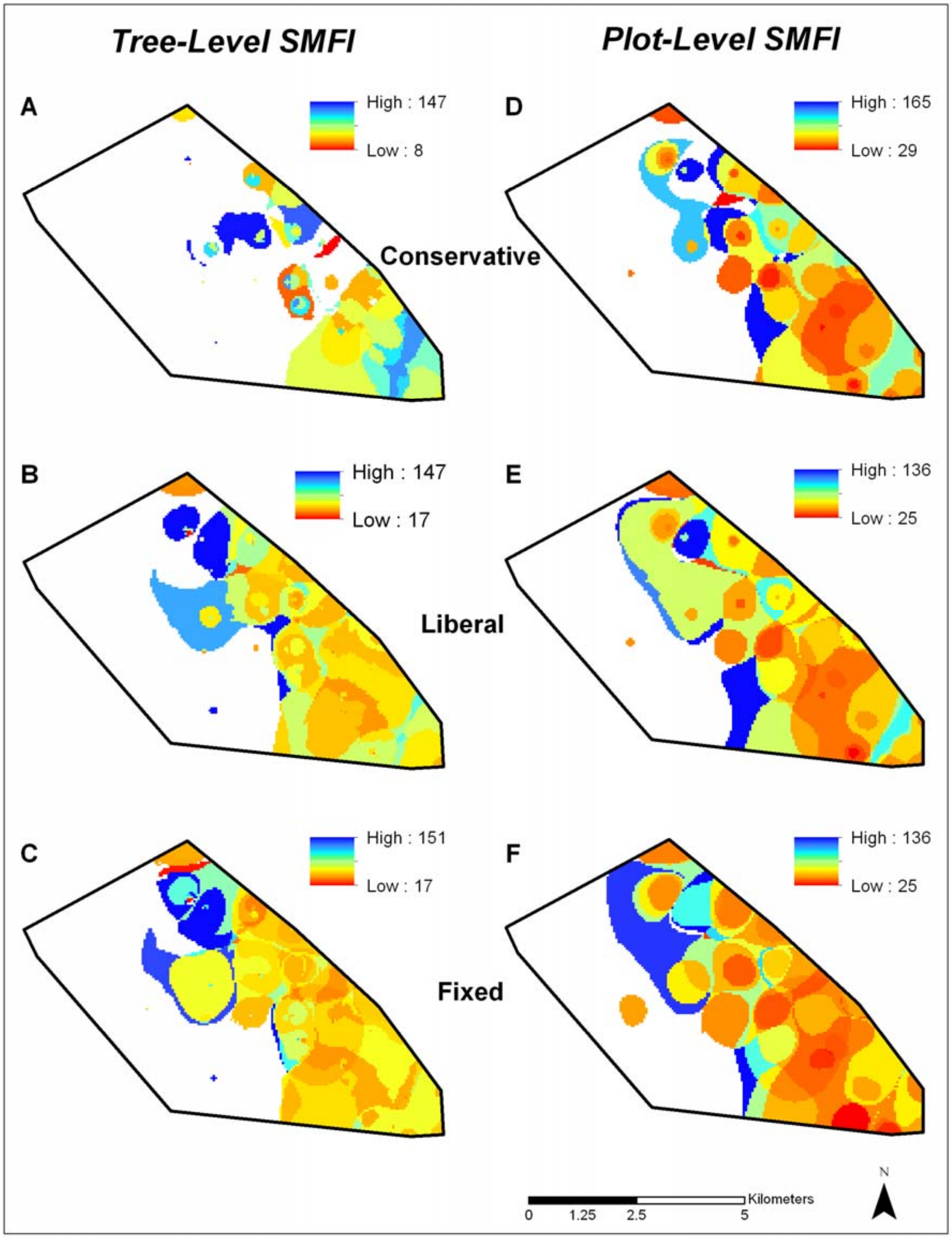

Figure 3.5 Comparison of tree-level (A-C) and plot-level (D-F) SMFIs as generated using conservative (A and D), liberal (B and E), and fixed (C and F) thresholds.

3.4 Discussion

3.4.1 Investigation I: The Effect of Cored Trees on Fire Boundary Estimations

Plot-level area burned estimates being larger than those at the tree-level are the direct effect of using the same number of nearest neighbours (n = 12, the default value in ArcGIS – see Hessl *et al.* 2007) in both analyses. Fewer numbers of potential plots as neighbours (n = 30 or 45) compared to potential trees as neighbours (n = 129 or 285) causes IDW interpolations to extend further distances to meet the minimum number of neighbours requirement. In turn, this stretches likelihood estimations, causing threshold-based fire perimeters, in this case, to be larger than for the tree-level analysis. Though this effect is problematic and should be addressed more thoroughly, it is not of major importance in this study. However, the difference of 569.7 ha in estimated area burned (approximately 21% of the overlapping area) between the traditional and modified datasets at the plot-level, and the even larger difference of 862 ha in estimated area burned (approximately 32% of the overlapping area) at the tree-level, are.

These differences highlight the importance of including cored trees when mapping historic fire boundaries, particularly if studies are taking place in and around areas dominated by mixed-severity fire regimes, or on the edge of areas dominated by high-severity regimes. By including cored trees as evidence for the absence of fire, not only did the SMFI remain virtually unchanged, indicating cored trees did not bias estimated spatial return intervals, but fire boundary estimates were "refined." Cored trees prevent potential overestimation of fire extent by limiting the distance to which likelihood interpolations are made, at least for any fires that occur during their lifetime. This is important not only for IDW interpolations, but for any spatial interpolation using nearest-neighbours as a baseline for analysis (e.g., Indicator Kriging), or for methods that define burn extent based on the proximity and arrangement of point locations (e.g., Thiessen Polygons).

3.4.2 Investigation II: Assessing Threshold Estimations Given Cored Trees

In both tree- and plot-level analyses, conservative threshold estimates produced the greatest number of polygons and the least total area burned; a direct result of smaller threshold values generating smaller fire boundaries, limiting the extent to which fires can burn. Smaller fires are less likely to overlap the boundaries of other fires, showing up as spotty, isolated events across the landscape. At the tree-level, this increased burn frequency in the areas closest to tree locations, but restricted the occurrence of fire from more remote areas, particularly during the rarer, widespread events (e.g., 1739, 1823, 1869 and 1886). In turn, longer fire intervals were removed from the landscape, shortening the overall SMFI. At the plot-level, however, the reduced number of potential recorders required IDW interpolations to extend further distances to meet the minimum number of nearest neighbour criteria, generating larger fire boundaries. As a result, conservative thresholds at the plot-level produced area burned estimations similar to liberal threshold estimates at the tree-level, while plot-level liberal and fixed thresholds reached even further than their counterpart tree-level analyses, causing extensive overlap of fire boundaries. Therefore, conservative fire intervals lengthened from tree-level estimations, while liberal and fixed intervals shortened as fire frequency across the landscape increased.

Relative to conservative threshold estimates, liberal thresholds produced a fewer number of polygons, a greater total area burned, and estimated longer return intervals; the result of larger threshold values generating larger fire boundaries, causing greater overlap between fires. As fire extent increases, individual fire events become more homogenized across the landscape, increasing the frequency by which areas of the landscape can burn. This is particularly apparent in areas of overlap between fire events. In widespread fires, liberal thresholds cause even larger portions of the landscape to burn. When these widespread events are rare, as in the case of high- and mixed-severity regimes, longer fire intervals become more numerous across the landscape and increase the mean return interval, as in the tree-level analysis. However, as fire extent continues to increase, as in the plot-level analysis, even greater overlap between fires occurs, further inflating the frequency of fire events across grid cells. In turn, this shortens the overall SMFI.

Though fixed thresholds did not generate the largest single area burned polygon, the average area burned in each fire exceeded average liberal estimates by 33.4 ha, explaining why fixed thresholds yielded the largest area burned estimates. This is evident in events when few scars recorded fires, but is particularly apparent when fixed thresholds generated burn polygons while conservative and liberal estimates did not. In these cases, conservative and liberal thresholds values were less than or equal to 0.03, and the percent of potential recorders per fire year (derived by dividing the number of recorders per fire year by the number of potential recorders for the analysis period) was equal to or exceeded 83%. However, burn polygons were generated for fire events in 1843, 1847, 1848 and 1879, which had conservative and liberal threshold values between 0.01 and 0.06, but percent recorders between 50% and 74%.

Fixed thresholds also produced the most linear relationship between percentage area burned and percentage scarred in tree- and plot-level analyses, yielding the greatest ability to estimate fire extent. However, all tree- and plot-level threshold estimations exhibited negative trending in each of their datasets, and consistently underestimated percent area burned. This is likely the result of two situations. First, when the percentage area burned exceeds the percentage scarred, as is the case for the largest, most widespread fires, particularly the 1869 fire, there may have been tremendous loss of potential recorders due to increased fire severity. However, these fires may have been so extensive that many trees survived and recorded the event along the fringes or in protected areas where fire severity diminishes, leaving behind a string of recorders across a large swath of the landscape. This situation may be exacerbated when fires start in and carry through the high elevations, and when climatic, micro-climatic, and/or topographic conditions prevent their spread down-slope to lower elevation forests.

Conversely, when the percent scarred exceeds percent area burned, as is the case for most of the fires recorded in the study area, and particularly in the mid- and lower-elevations, infrequent large and severe fires may remove recorders of past frequent, less-severe fires from the landscape. In areas dominated by mixed-severity fire regimes, this can restrict the interpretive power of these smaller fire events to confined, isolated locations within the landscape. Though the ratio of percentage scarred relative to percent area burned is heightened in tree-level analyses by an increased number of replicates per plot, the similar trend at the plot-level gives strength to this argument.

These results indicate the degree to which IDW interpolations are influenced by the number of potential recorders (acting as nearest neighbours in this case), and highlight the importance of using fixed thresholds when mapping small, isolated fire events, particularly at the tree-level. Conservative thresholds, calculated from a bolstered number of potential recorders due to the inclusion of ring-width series from cored trees, consistently indicated isolated, spotty fires across the study area **(Figure 3.6)**, a situation that is particularly problematic when fire-scars are proximally close together and likely from the same fire event. Liberal thresholds, calculated from the number of fire-scars relative to the number of potential recorder trees, showed more contiguous fire boundaries across the study area, yet shared with conservative thresholds an inability to discriminate fire boundaries in the smallest fire events. As such, variable threshold calculations, such as the conservative and liberal variants described here, may not apply enough importance to fire-scar evidence when the number of recorders far outweighs the number of scars, therefore neglecting to generate area burned estimates. In this situation, fixed thresholds help eliminate the bias instilled by a large number of potential recorders relative to fire-scars. However, using only fixed thresholds can potentially over-estimate burn extent in intermediate and larger fire events.

Based on the outcomes of the sensitivity analysis of threshold values, I suggest a combination of thresholds for studies taking place in and around areas dominated by mixed- and high-severity fire regimes. Liberal thresholds should be applied for all analyses, as these provide more contiguous and thus more ecologically meaningful results than conservative

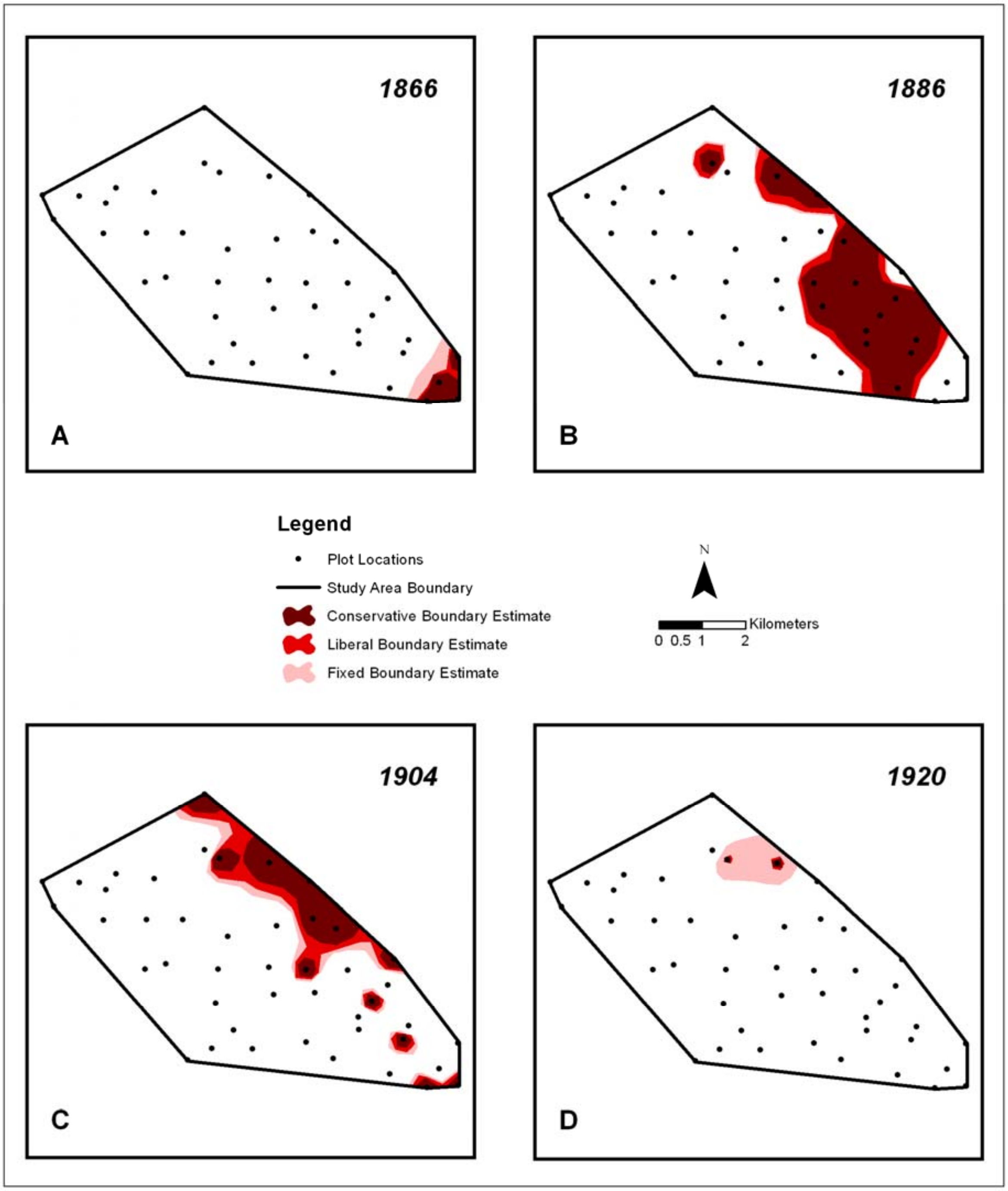

Figure 3.6 Examples of the "spotty" nature of conservative boundary estimates relative to liberal and fixed estimates at the plot-level. Results are for fires in (A) 1866, (B) 1886, (C) 1904 and (D) 1920.

estimates. Furthermore, these results do not suffer from potential over-estimation to the degree that fixed thresholds do. For fire boundaries that fail to generate due to a limited number of fire-scarred samples relative to potential recorders, apply fixed thresholds of no more than 0.5, as these will give greater interpretive power to fire-scar evidence.

3.4.3 Investigation III: SMFI vs. MPFI and CMFI Statistics

Though SMFI did not vary greatly between analyses in this study, it exceeded both MPFI and CMFI in all threshold calculations, which differs from the results obtained by Kernan and Hessl (2010). Using fire-scar data from the Okanogan-Wenatchee National Forest of central Washington, USA, Kernan and Hessl (2010) found the SMFI produced estimates of spatio-temporal variability lying between MPFI, a minimum measure, and CMFI, a maximum measure, based on fire-scar analyses. However, their study did not take place explicitly in areas dominated by mixed- and high-severity fire regimes, nor did they include cored trees as proxies for the absence of fire.

High-severity regimes are characterized by stand-replacing fires with long, infrequent return intervals, while mixed-severity regimes are characterized by mosaics of more frequent low- to moderate- severity, stand-maintaining fires, but are subject to intermittent high-severity fires (Agee 1993, Schoenaggel et al. 2004). Point data taken from fire scars in areas dominated by these regimes will reflect longer mean return intervals than areas dominated by low-severity regimes. In general, however, the number of fire scars decreases with an increasing elevational gradient, as fire behaviour also tends to increase in severity with increasing elevation (Agee 1993). In turn, previous evidence of fire is removed from the landscape, leaving behind a sample base that can bias broader scale return intervals in favour of the more frequent, less-severe fires inherent to the lower elevations. SMFI calculations offset this effect by giving greater interpretive power to fire scar evidence in higher elevations, likely reflecting longer return intervals inherent to the regimes to which they are subjected. SMFI results should, in turn, reflect longer return intervals than CMFI or MPFI.

Furthermore, cored trees suppress estimated burn extent in areas adjacent to fire-scarred trees while they are alive and actively recording the absence of fire. In years when cored trees are not active recorders, IDW interpolations extend to further reaches to satisfy the minimum number of nearest neighbours. In this situation, the fire-scarred trees closest to the cored trees will contribute most of the temporal information, spreading their influence across longer distances, and increasing the number of grid cells they affect. With approximately 36% of study plots and over half the dataset including cores from trees in high elevations, and with several isolated, high-elevation sites with long fire histories, each contributing long return intervals, SMFI results should reflect longer intervals than MPFI and CMFI.

3.4.4 Application in Mixed-Fire Landscapes

In landscapes dominated by mixed-severity regimes, including tree core data in reconstructions of historic fire boundaries as proxies for the absence of fire provide "refined" estimates of fire perimeters and area burned. While actively recording the absence of fire, tree core information limits the extent to which nearest neighbour interpolations are made, preventing fire perimeters from protruding into areas dominated by less-frequent, high-severity fires, which can bias subsequent analyses in favour of more frequent fires.

Hessl et al. (2007) found that area burned estimates produced by IDW interpolations may be underestimated, particularly in cases where the presence of unscarred recorders outweigh scarred recorders, indicating either complex fire boundaries or burn severities too low to scar some trees. My results support this finding, but for different reasons. Complex fire boundaries are inherent to mixed-severity fire regimes. However, areas subject to a mix of fire severities can also experience an unequal proportion of unscarred recorders relative to scars due to the loss of the record by subsequent high-severity fires. In the former situation, a gridded, fine-resolution sample design can aid in defining complex fire boundaries. In the latter, applying a fixed threshold in analyses can bolster evidence that may otherwise be overshadowed. Collecting corroborative evidence of fire, including the presence/absence of charcoal on each tree and in the surrounding soil, and assessing the position and morphology of each scar strengthens the case for fire in face of low sample densities, and justifies the application of fixed thresholds in these situations.

As Kernan and Hessl (2010) revealed, SMFI can supplement traditional statistical methods that summarize fire return intervals at discrete point locations (e.g., Mean Point Fire Interval - MPFI, Composite Mean Fire Interval – CMFI), which are subject to false negatives or are scale sensitive. The benefit of an SMFI is its ability to illustrate spatial heterogeneity; whereas MPFI and CMFI generalize temporal variability to a single number at fixed locations, an SMFI interprets finer-grained fire patterns across a landscape (Kernan and Hessl 2010).

In mixed-severity fire regimes, and in areas adjacent to high-severity regimes, an SMFI may further enhance traditional point data by giving stronger interpretive power to fire-scar evidence in higher elevations. When applied across a landscape, this information may reflect more accurate interpretations of return intervals, providing forest and fire mangers with more meaningful, spatially interpretable information.

Chapter 4: Conclusion

4.1 Temporal and Spatial Variation of the Historical Fire Regime

The fire history of the Darkwoods indicates return intervals were similar to other studies in mixed-severity fire regimes in southeastern British Columbia; particularly in relation to the fire histories of the Joseph and Gold Creek watersheds in the east Kootenays. Furthermore, fire-free intervals exceeded all calculated WMPI for fire history plots, indicating a strong fire exclusion effect in the study area during the 20th century.

Differences in spatio-temporal controls on the occurrence of fire between tree- and plot-level analyses reveal the degree to which bottom-up and anthropogenic influences have affected the fire regime of the Darkwoods. Elevation is the pre-dominant broad-scale control on fire occurrence within the southeastern-most watershed. However, tree-level variation indicates slope aspect and slope steepness are also strong controls, reflecting the degree to which complex topography and microclimatic conditions affect the behaviour of individual fire events. Between the different periods of anthropogenic land-use, the likelihood of fire occurrence did not vary significantly until after 1945, when modern methods of fire-suppression were introduced; at this point the likelihood of fire occurrence was greatly diminished. Furthermore, fires were more likely to occur in increasingly warmer aspects after Euro-American settlement in the 1850s. The exact reasoning behind this trend is not certain, but may be attested to a changing global climate in the post-industrial era; southern aspects may be heating up and drying out more so than pre-industrial conditions would allow, facilitating an increased likelihood of fire in these areas.

The current British Columbia NDT classification schema does not accurately capture variations in fire frequency and severity in the Darkwoods; particularly in reference to recently designated ICHmw4 variant and ESSFdm subzone in the west Kootenays. Out of six potential changes using the five-class NDT schema as it currently exists, only the configuration that classified the entire ICH zone as NDT4 (includes ICHxw, ICHdw1 and ICHmw4) and the ESSFdm subzone as NDT3 accurately represented the variation of the mixed-severity fire regime. Even with this change, however, two plots in the ESSFdm zone with long and robust fire histories remained misclassified, indicating the current five-class NDT schema is incapable of capturing the full range of variability in fire severities. I suggest NDT classes be modified to better represent the documented presence of mixed-severity fires in southeastern British Columbia, specifically that the ICHmw4 and ICHdw1 BEC variants be reclassified as NDT4 and that descriptions of NDT3 and NDT4 be modified to acknowledge the importance of mixed-severity fires regimes.

4.2 Mapping Historical Fire Boundaries in Mixed-Severity Fire Regimes

GIS is becoming increasingly important to fire historians as a tool to recreate spatial patterns of fires across landscapes. In landscapes dominated by mixed-severity fires, including tree core data in reconstructions of historic fire boundaries as proxies for the absence of fire yields “refined” estimates of fire perimeters and area burned. This information prevents the overestimation of fire boundaries into areas where evidence indicates fires did not occur.

Small fire events are also important components in understanding mixed-severity fire regimes. As such, including fixed-thresholds to calculate the smallest fire boundaries, particularly when the presence of unscarred recorders far outweigh scarred recorders, gives stronger interpretive power to fire-scar evidence. The lack of recorders does not necessarily mean fires were small and insignificant; in mixed-severity regimes, the lack of fire-scar evidence may reflect the residual effect of intermittent, high-severity fires removing recorders from the landscape.

Traditional statistical methods that summarize fire return intervals at discrete point locations (e.g., MPFI and CMFI) may be subject to false negatives or may be scale sensitive (Kernan and Hessl 2010), potentially underestimating fire occurrence. In mixed-severity fire regimes, however, fire histories reconstructed purely from fire-scar data may bias broad-scale assessments in favour of shorter return intervals. This is particularly problematic when areas between sampled points are not assessed, and especially if these areas experience more severe fire behaviour at longer return intervals. Consequently, fire-scar data may suggest management practices that too frequently disturb forests in these areas. Spatial mean fire intervals (SMFI) can supplement these traditional statistical methods by interpolating between sampled points. Including tree core data in SMFI analyses is especially powerful for areas dominated by mixed-severity fire regimes, as they limit the extent of interpolations, reducing the number of fires and lengthening subsequent fire intervals across the landscape. The SMFI of the Darkwoods exceeded both MPFI and CMFI, reflecting the degree to which a mix of high-severity, stand-replacing fires, intermixed with low- and moderate-severity, stand-maintaining fires, can lengthen mean return intervals across a mixed-fire landscape.

4.3 Management Implications

In the Darkwoods, management decisions must consider scale and location as the most important factors in managing their forests. Disturbances varied greatly between tree-level and plot-level assessments, and these assessments varied greatly among themselves depending on their locale within the landscape. Mixed-severity fires are complex by nature, and require similarly complex management strategies. With intentions of managing the landscape for specific wildlife species, this is particularly important. Wildlife utilize the land in different ways and at different scales, so understanding their habits will aid in developing strategies that best suit their needs.

The degree to which fire exclusion has impacted the landscape should also weigh heavily in management decisions. At least 40% of the study area in southeastern-most watershed is outside its historic range of variability, making the landscape highly susceptible to fire. Logging practices of the past century may have offset this to a degree, but their specific strategies may have inhibited the forests resilience to fire. Further analysis will be necessary to assess the degree and direction in which these practices have affected the modern fire regime.

4.4 Future Analysis

The fire-climate relationship of the Darkwoods fire regime is currently unknown. Future analysis will require methods such as superposed epoch analysis (SEA) to tease out local from regional signals, and to discern which climatic signals potentially have the greatest influence on the occurrence of fire (after Daniels et al. 2011, DaSilva 2009). Furthermore, the stand dynamics inherent to this portion of the Darkwoods require further assessment.

Cohort assessments in both the over- and under-story are needed to determine the degree to which forest structures have changed as a result of fire suppression, as well as to quantify the percentage of plots that fall under a mixed-severity fire regime (after Nesbitt et al. 2010). Additionally, future mapping methodologies must implement nearest neighbour interpolations that are more ecologically meaningful to the study area. This can be accomplished by assessing the extent of spatial autocorrelation among sample points (e.g., trees or plots). Combined with the new knowledge about fire in the Darkwoods presented in this thesis, the proposed future analyses will contribute to a regional understanding of historic fire regimes and contemporary forest and fire dynamics in the Kootenay region.

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