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Wildfire Risk to Parks Canada town sites in Banff, Yoho, Kootenay, Jasper, Waterton Lakes, and Riding Mountain National Parks

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Executive Summary

Wildfire is a common natural disturbance throughout the boreal and cordilleran ecozones of western Canada and is likely to increase in frequency and severity under climate change. Fires that occur in the mountain parks can burn tens of thousands of hectares forest in a single event and have recently shown the capacity to burn more than 30km in a single overnight fire run. This kind of fire behaviour potentially puts town sites, and the people who live in them at tremendous risk.

To support sound fire mitigation measures to minimize the wildfire risk to these communities, it is important to know the likelihood of wildfire occurrence across the landscape, and what management actions could minimize this hazard. This project was designed to use the Burn-P3 model to determine the spatial variation in burn probabilities and potential wildfire characteristics across the individual landscapes of Waterton Lakes, Banff, Kootenay, Yoho, Jasper, and Riding Mountain National Parks. More specifically, the project seeks to answer the following questions:

A) What is the burn probability surrounding the communities within the Parks?
B) What is the wildfire hazard (probability and intensity) to these communities?
C) Where do the fires that threaten communities originate from? What is the spatial extent of the fire threat zone (namely the fireshed)?
D) What is the seasonal variability in all the above measures?
E) What has been the effectiveness of the fuel management strategies in Banff National Park?
F) How has Mountain Pine Beetle affected the burn probability of Jasper National Park?
G) What are the fire source-sink dynamics in Banff, Yoho, and Kootenay National Parks?

We conducted four distinct, coarse scale, baseline burn probability assessments on Waterton Lakes National Park (WLNP), Jasper National Park (JNP), Riding Mountain National Park (RMNP), and Banff/Yoho/Kootenay (BYK) combined. We modeled the burn probability (BP), fire hazard, and firesheds affecting the communities of Waterton Townsite (WLNP), Town of Jasper (JNP), Wasagaming (RMNP), and Town of Banff, Lake Louise, and Field (all in BYK).

Results showed distinct differences in burn probability, hazard, and firesheds due to the influence of seasons, resulting primarily from changes in the fuel complex throughout the year, specifically from grasses (which vary in degree of curing), and the leaf-out stages of aspen forests. Burn probability and hazard were spatially heterogeneous across all landscapes modelled. Due to the complex topography of rocky ridges dissecting the forests of WLNP, JNP and BYK we found that the firesheds affecting the communities to be locally constrained. While RMNP has much simpler topography, its fireshed was also restricted to the local area as the surrounding agricultural landscape serves as a significant protective shield against wildfires. The fuel treatments in Banff National Park, which include both mechanical treatments and prescribed fire, have had mixed results in terms of their effects on potential fire behaviour, in some locations fire likelihood appears to have increased, but this is mostly due to the difficulties associated with using the coarse FBP system to describe relatively subtle changes in fuel resulting from management actions. Most importantly, however, the fuel treatments immediately surrounding the Banff town site have reduced the potential fire intensity that would occur, thereby increasing the likelihood of successful fire suppression in these key locations. In Jasper, the mountain pine beetle epidemic has increased the risk of wildfire to an alarming level, however, this is an ephemeral situation that is dependent upon the presence of red-needled dead trees; as the needles fall from the trees, the hazard will decline, however it will still be elevated from the pre-infestation situation.

Project Staff

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Scott Murphy works for Parks Canada out of their Halifax office and is the lead for wildfire risk reduction and prescribed fire for the Agency. At the time this project began he was the Fire Management Officer based out of Waterton Lakes National Park. He has more than 15 years of experience dealing with prescribed fire planning and execution, fuel treatments, and risk assessments.

1. Introduction

The mountain national parks of the Canadian Rockies were designated a UNESCO World Heritage Site in 1984 for their unique splendor. Every year these parks capture the imagination of millions of visitors from around the world and as such, they are an important economic driver to the region, the Province of Alberta, and for the Parks Canada Agency. However, the townsites and extensive visitor facilities located within the mountain parks are nestled in densely forested zones that are at risk of burning or being severely affected by wildfire. Parks' managers must contend with the responsibilities and difficulties of protecting high values at risk, such as human lives and infrastructure, while at the same time fulfilling the primary mandate of the Parks Canada Agency, which is to maintain the ecological integrity of ecosystems and habitats.

Wildfires are common throughout the western Canadian cordilleran forests, and many of these forest ecosystems are adapted to recurrent burning. While the amount of forested area that burns each year varies considerably, sources show that there has been a substantial reduction in annual area burned over the past century coinciding with the European colonization period (Arno 1980; Arno and Gruell 1983; Stockdale et al. 2019a). European settlers changed the natural disturbance dynamics of the entire landscape by essentially excluding fire through the forcible removal of Indigenous people and their fire management practices, and the introduction of fire suppression policies (Stockdale et al. 2019b). Due to the changes in the disturbance regime of the region here has been substantial increases in later successional vegetation types, increases in total forest cover, and the loss of meadows and open canopy woodlands throughout the Canadian Rocky Mountains (Stockdale et al. 2019b). With these changes in vegetation cover, there has been an increase in the potential for high severity wildfires (Arno et al. 2000; Stockdale et al. 2019a). So too, when this changed vegetation complex is combined with favorable weather for wildfire activity as we have experienced regularly since the 2000s, wildfires are prone to explosive burning behaviour notably during strong and sustained winds.

Destructive wildfires have occurred with increasing frequency in the past 20 years. Most recently we have seen the massive blazes in British Columbia in 2017 and 2018, and in Alberta

in 2017 (Kenow fire in Waterton Lakes National Park), 2016 (Fort McMurray fire), 2011 (Slave Lake fire), and the 2003 fires in Kelowna and Barriere in British Columbia, and Blairmore Alberta. Other large, and long burning fires have occurred in on the boundaries of Banff National Park over the past several years that may have avoided burning significant human infrastructure, but certainly had the capacity to be very destructive with as little as a shift in wind direction or speed. Nor are these extreme fire events restricted to the provinces of Alberta and British Columbia, as we have seen both higher fire intensities severities currently observed across North America (Stephens et al. 2014; Schwartz et al. 2015).

Given the long history of fire occurrence in the mountains, it is likely not a matter of *if* a fire will spread near mountain communities, but rather *when*. As such, we need to understand what will happen if fires occur near these communities, and what we can do to lower that risk. As the mountain national parks attract millions of visitors each year during the summer months, and are home to thousands of permanent residents, wildfire preparedness is of outmost importance to protect lives, minimize the risk to the public, protect the necessary infrastructure contributing to the economic health of those regions, while at the same time maximizing the ecological benefits wildfire contributes to the landscape. In this regard, it is imperative for land managers to quantify wildfire risk to communities, to identify fire impacts on values at risk, to determine fire hazard thresholds at which various fire control tactics need to be employed, and to identify fuel management measures, as well as the efficiency of those measures, for protecting communities.

Due to the distribution of wildfire being a semi-random probabilistic event, it is difficult to predict when and where future wildfires will occur. Fortunately, with the use of computer fire growth models such as Prometheus (Tymstra et al. 2010) and Burn-P3 (Parisien et al 2005) that are informed by established knowledge on fire weather, fuel conditions, drought codes and indices, as well as probability distributions of past lightning and human fires, it is possible to examine burn probability to highlight regions most at risk of wildfire. These models can also inform on the overall fire risk zone to a community by identifying the maximum spread distance and direction potential wildfire threat can originate from (this is called the fireshed). This framework of analysis also enables managers to test different scenarios (changing ignition

patterns, fuel, or weather conditions) to determine how much these might alter the burn probability surrounding key values on the landscape.

To manage wildfire so that ecological benefits are maximized and the risk to the public is minimized, managers need to be able to understand what parts of the landscape are most likely to burn, what conditions they may burn under, what the potential fire behaviour and impacts may be, and what the thresholds may be at which different fire control tactics need to be employed. Wildfire hazard (the combination of the likelihood of occurrence and the intensity of fire (Calkin et al. 2010)) is highly variable across space and time (Miller and Ager 2013; Scott et al. 2013) and can also be modeled using Burn-P3 (Parisien et al. 2005; Parisien et al. 2007, 2011, 2013; Miller et al. 2008; Wang et al. 2014, 2016; Whitman et al. 2017). Burn-P3 is a model that uses a Monte-Carlo approach to simulate a large number (thousands) of fires across the landscape to provide information that managers can use to identify mechanisms driving wildfire risk in different parts of the landscape. Burn-P3 simulates the spread of fires using the Prometheus fire growth model (Tymstra et al. 2010) on a gridded landscape with known fuels and topography. Burn-P3 uses probabilistic draws of ignition locations and fire weather conditions. For many years the output of individual model runs were displayed as a single burn probability map (Parisien et al. 2005, Beverly et al. 2009, Beverly and McLoughlin 2019), however this approach tends to oversimplify a very complex problem; numerous maps and model outputs are required to adequately present wildfire risk information. To do so, source data must be probed further, and multiple model outputs must be examined in order to gain a fuller understanding of wildfire risk.

To describe wildfire risk, we need to know the impact fires will have on highly valued resources and assets (HVRAs) (Calkin et al. 2010; Thompson et al. 2011). Fire can have positive impacts include the creation of diverse forest age-class structures, regeneration of fire-dependent plants, and the creation of habitat for early seral stage species, among others (Johnson 1996). However, fire can also have negative impacts which include, but are not limited to, the loss of human life, destruction of houses, and the loss of key ecological communities and breeding, denning, and feeding habitat for various wildlife species (Thompson et al. 2011). In general, parks and protected areas have a difficult task set before them. Because the

cordilleran forest is home to numerous wildlife, plant, and other species which directly or indirectly depend upon the physical effects of fires, Parks Canada has a clear mandate to protect ecological integrity, which includes using wildfire to achieve these ecological objectives. However, fire cannot be allowed to burn indiscriminately because human life, communities and infrastructure all need to be protected from fire.

This technical report presents the results of extensive fire spread modelling scenarios to assist fire and land managers in understanding probabilities of wildfire risk near the communities of Banff (AB), Lake Louise (AB), Field (BC), Jasper (AB), Waterton (AB), and Wasagaming (MB). The report includes study objectives, a detailed study area description, fire growth modeling methods, and wildfire risk and hazard outputs. The study area description includes the topographic setting and general environment, dominant forest ecosystems, climate conditions, historical and contemporary fire regimes, and popular recreational activities in the parks and their infrastructure.

Goals and Objectives

The objectives of this study were to investigate the following questions:

A) What is the burn probability across Banff, Yoho, Kootenay, Jasper, Waterton Lakes, and Riding Mountain National Parks, and surrounding the communities within them?
B) What is the wildfire hazard (probability combined with intensity) to these communities?
C) Where do the fires originate that threaten these communities (what is the fireshed)?
D) What is the seasonal variability in all the above measures?
E) For the Banff-Yoho-Kootenay (BYK) landscape we investigated the impact of their historic prescribed fire and fuel treatment programs on the above questions.
F) For Jasper National Park we examined the impact of mountain pine beetle (MPB) killed forests on the burn probability of the landscape
G) In BYK we investigated fire source-sink dynamics to identify the areas of the landscape where the most damaging fires (to communities) originate.

2. Study Area

We conducted our study over four spatially distinct modeling domains (Figure 1), the first three of which contain Rocky Mountain national parks in Alberta and British Columbia, while the fourth is in Manitoba. These domains were: A) Waterton Lakes National Park (WLNP); B) Banff, Yoho, and Kootenay (BYK) National Parks combined; C) Jasper National Park (JNP); and D) Riding Mountain National Park (RMNP) (Table 1). The three Rocky Mountain modelling domains are all along the Continental divide in Alberta or British Columbia. Most of these Parks and surrounding landscapes are forested, although a significant portion of the eastern edge of WLNP and its buffer zone is in the grasslands. RMNP is at the southern limit of the boreal forest in Manitoba, and the surrounding landscape is largely under agricultural land use. The landscape surrounding the mountain parks are either provincial parks, commercial forest holdings, grazing and farming lands, communities, or other forms of private ownership. Each of these modeling domains will be described in further detail in their own sections of the report.

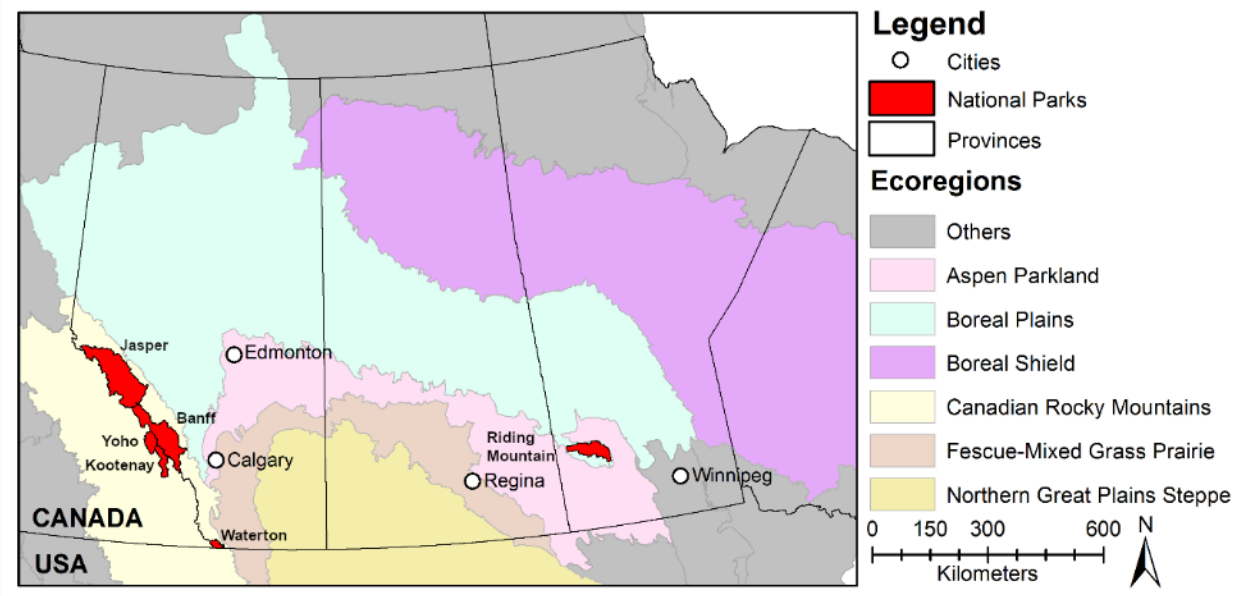

Figure 1. Location of the National Parks within Manitoba (Riding Mountain), Alberta (Waterton Lakes, Banff, and Jasper), and British-Columbia (Yoho and Kootenay) as well as their associated ecoregions within Canada.

Table 1. Modeling domains of the Canadian National Parks Wildfire Risk Assessment including the sizes of the National Parks and their surrounding buffers, communities with permanent resident populations, 2017/2018 park attendance and the increase from the previous year. Note: population figures do not include transient worker populations and tourists, which if included would increase populations significantly.

National Park Modeling Domain	Size (km^2)	Buffered size (km^2)	Communities	Population (approx.)	Park Attendance 2017/18 (Δ2016/17)
Waterton Lakes	505	2,812	Waterton	100	568,807 (+6%)
Banff Yoho Kootenay	9,360	20,587	Banff Lake Louise Field Canmore	9,000 1,000 150 14,000	4,181,854 (+3%) 712,046 (+3%) 531,009 (+2%) NA
Jasper	10,878	20,563	Jasper	4,500	2,425,878 (+3%)
Riding Mountain	3,089	6,972	Wasagaming	<50	423,146 (+19%)

Jasper, Banff, Yoho, and Kootenay National Parks

While Jasper was modeled separately from Banff, Yoho, and Kootenay, due to being contiguous with these other parks, the general information for all these parks is presented below for these parks combined (see Figure 2 and Figure 3).

General description.

Jasper, Banff, Yoho, and Kootenay are adjoining National Parks situated in the Canadian Rockies and encompass some of the most rugged mountain environments. Both Yoho and Kootenay National Parks, covering a combined area of 2,719 km^2, lie against the west side of the Continental Divide and include the Main and Western Ranges of the Canadian Rockies, while Banff National Park (BNP) covers 6,641 km^2 of Rocky Mountain Main and Front Ranges along the east slopes of the Continental Divide. Jasper National Park lies immediately to the north of Banff National Park and covers 10,878 km^2. These four contiguous iconic national parks comprise 20,238 km^2 of protected mountain ecosystems. The lowest elevations of BNP start at 1345 m and are found in the Bow Valley along the eastern park boundary. In contrast, the highest elevations are found to the west along the Continental Divide and reach 3612 m (Mount Forbes). The western parks share similar attributes where the elevations of Yoho National Park (YNP) range from 1097 m to 3567 m (Mount Goodsir), while those of Kootenay National Park (KNP) range between 1000 m and 3424 m (Mount Deltaform). The lowest

elevations in both YNP and KNP are found along the western park boundary in the Kicking Horse and Sinclair Valleys, respectively. Jasper National Park's lowest point is at 985 m at the East Gate, and its highest point is the summit of Mount Columbia at 3747 m.

Forested areas within these parks are heavily dissected by rocky ridges and glaciers that form nearly 50% of the total land base. Treeline elevation is variable based on aspect, and ranges from 2100 m to 2300 m. The ecological land classification of the mountain parks into biophysical units includes three distinct ecoregions: Montane, Subalpine, and Alpine (Coen and Kuchar 1982; Holland and Coen 1982; Achuff et al. 1984). The Montane ecoregion coincides with lands below 1600 m, whereas the Alpine represents landforms and sparse vegetation above treeline. The elevation around 2000 m denotes the separation between the Lower and Upper Subalpine, which is commonly separated for ecosystem management purposes by the Parks Canada Agency. Ecoregions differ not only by their elevations, but also by their landforms, vegetation and tree species assemblage, soils, and meso-climate conditions.

All parks are traversed by major highways following valley bottoms and treed mountain passes. BNP and YNP also have an active rail line with up to 30 trains per day. The Trans-Canada Highway runs through Banff and Yoho National Parks, and through the communities of Canmore, Banff, Lake Louise, and Field. The Yellowhead Highway runs through Jasper National Park, and the community of Jasper. The contiguous National Parks landscapes including Jasper National Park were established as a UNESCO World Heritage Site in 1984.

Biogeoclimatic Description

Vegetation

This is a general summary of the main tree species encountered in all three mountain parks. For a detailed description of species assemblage found at the ecosite level, we recommend the reader to consult the Ecological (Biophysical) Land Classifications reports (Coen and Kuchar 1982; Holland and Coen 1982; Achuff et al. 1984). Lodgepole pine (*Pinus contorta*) is the dominant species in the mountain parks. It can be found at all elevations and notably on warmer facing slopes. Both aspen (*Populus spp.*) and Douglas-fir (*Psuedotsuga menziesii*) trees are constrained to the Montane (often coinciding in high-biodiversity open canopy woodlands) and occasionally to the lower elevations of the Lower Subalpine. Douglas-fir trees tend to

establish on xeric sites. In contrast, spruce (*Picea spp.*) stands are normally found on cooler aspects and at valley bottom where soils are more mesic. White spruce (*Picea glauca*) trees prevail in the Montane, while Engelmann spruce (*Picea engelmanii*) and subalpine-fir (*Abies lasiocarpa*) trees are commonly found together in the Subalpine. Scattered alpine larches *(Larix spp.*), as well as limber (*Pinus flexilis*) and whitebark pines (*Pinus albicaulis*) commonly grow near treeline. Both limber and whitebark pines are designated as Species-At-Risk in Alberta with whitebark pine being designated as an endangered species under the federal Species at Risk Act. With the exception of spruce and fir trees, all tree species are fire-adapted and have coping mechanisms to survive light surface fires to intense stand-replacing fires.

Within the forested area, shrubby and grassy meadows are common throughout the mountain parks and largely occur along flat valley bottoms and low angled slopes. Well-drained and well-grazed meadows will tend to be maintained as grassland, whereas those that are poorly drained, such as muskegs, will contain either a large component of shrubs or small trees. The ruggedness of the landscape and steep angled slopes produce avalanche paths vegetated by shrubs, forbs, and grasses, which dissect the forest cover and can affect fire behavior and the rate of fire spread.

Above treeline, extensive alpine meadows exist largely as heath tundra. Most meadows do not have enough continuous cover of tall grasses or forbs to sustain wildfire spread over mountain passes or some significant distances into nearby forests.

Biogeoclimatic Classification

Banff National Park encompasses two Natural Regions: the Rocky Mountains and the Foothills (Natural Regions Committee, 2006). The Rocky Mountain Natural Region is divided into three subregions: the Alpine at high elevation; the Montane at lower elevation; and Subalpine in between at mid-elevation. The Rocky Mountain Foothills Natural Region is divided similarly by elevation into the Upper and Lower Foothills. See Figure 2.

Yoho and Kootenay National Parks are classified under British Columbia's Biogeoclimatic Ecological Classification system. Five zones are included within the region of interest which can be regrouped into classes similar to the Alberta Natural Regions. Zones such as Mountain Spruce (MS) and Interior Douglas-fir (IDF) remain their own but Engelmann Spruce – Subalpine

Fir (ESSF), and Interior Cedar – Hemlock (ICH) have been regrouped under the umbrella of Alpine/Subalpine for the purposes of this modeling exercise. The IDF (variant “xk”) has very dry conditions at valley bottoms cool winters and hot summers with moisture deficits. Paper birch (*Betula papyrifera*), black cottonwood (*Populus trichocarpa*), white-, and Engelmann spruce are most common in moister sites. The various ecological zones present in the mountain Parks are shown in Table 2 and Figure 2 and Figure 3.

Table 2. Characteristics of the Alberta Natural Subregions (NSR) (Natural Regions Committee 2006) and Biogeoclimatic Ecological (BEC) zones in British Columbia (MacKillop et al. 2018) within the Rocky Mountain National Parks. Also see Figure 2 and Figure 3.

Ecological Classification Zone	Key characteristics
Alberta Natural Subregions	
Alpine	Cold, wet, and herbaceous shrublands at high elevations within the Rocky Mountains between glaciers and snowfields.
Subalpine	Short cool summers with high winter snowfall. Mixed conifer with Lodgepole pine (*Pinus contorta*) and Engelmann spruce (*Picea engelmanii*) forests. Open stands of Engelmann spruce and subalpine fir (*Abies lasiocarpa*) at higher elevation and closed lodgepole pine at lower elevations.
Montane	Cool summers with relatively warm winters al lower elevation. Northern aspects are dominated by mixed deciduous stands of aspen (*Populus tremuloides*), lodgepole pine, Douglas-fir (*Pseudotsuga menziesii*) and white spruce (*Picea glauca*). On southern aspects dry warm grasslands. At higher elevation forest cover is closed mixedwood coniferous (lodgepole pine) dominated forests.
Upper Foothills	Short wet summers with snowy cold winters. Grassland foothills with closed coniferous forests (lodgepole pine, black spruce (*Picea mariana*), white spruce) on steeper slopes and higher elevation.
Lower Foothills	Area of transition between the Boreal cold winters and Cordilleran high winter snowfalls on plateaus and rolling uplands, of closed mixedwood forests (aspen, lodgepole pine, white spruce, balsam poplar (*Populus balsamifera*).
Foothills Parkland	Cool summer and short growing season on sloping lower foothills and hummocky uplands dominated by grasslands (fescue) and aspen forests in mesic valley bottoms.
British Columbia BEC Zones	
IDFd(x)k Interior Douglas-fir	Very dry cool winters with shallow to moderate snowfall and hot dry summers. Low tree productivity due to site moisture deficits. Low conifer diversity mostly dominated by Douglas-fir and lodgepole pine with grassy understory.
MSdk Montane Spruce Dry & Cool	Transitional zone between IDF to ESSF. Cold short winters and dry warm summers. Dominated by post-fire even aged stands of lodgepole pine, interspersed with mixedwood forests including subalpine fir, Douglas-fir, trembling aspen, western larch (*Larix occidentalis*), Rocky mountain maple (*Acer glabrum*), paper birch (*Betula papyrifera*) and western redcedar (*Thuja plicata*).
ICH Interior Cedar – Hemlock	Highly productive due to warm moist summers. Mostly conifer dominated mixedwood forests of western red cedar, subalpine fir, lodgepole pine, Douglas-Fir, trembling aspen, and western larch.
ESSFdk Engelmann Spruce – Subalpine Fir Dry & Cool	Moist cold winters with very deep snowfall and wet cool summers. Dominated by Engelmann spruce and subalpine fir, interspersed with lodgepole pine and Douglas-fir with some alpine larch, whitebark (*Pinus albicaulis*) and limber pine (*Pinus flexilis*).

Climate Description

According to the Köppen Climate Classification Map (Peel et al. 2007) of Canada, BNP falls under a continental subarctic climate (Dfc) with cool summers and year-round precipitation, whereas the National Parks to the west of the Continental Divide, as well as the southern end of BNP, are classified as a humid continental climate (Dfb) with mild summers and wet all year. The Continental Divide plays an important role in regulating the amount of precipitation received. The east side of the Divide, being on the lee side of the mountains, receives far less precipitation than the west slopes, which are subjected to moist Pacific air masses that deposit large amounts of precipitation (rain or snow) due to the orographic effect of the mountains. Some general climate information for the mountain Parks is shown in Table 3.

In a mountain environment, regardless of its position against the Continental Divide, the effect of topography plays an important role on temperatures, relative humidity levels and amount of precipitation received (Janz and Storr 1977). Shadows cast by high mountains and ridges, can maintain cooler temperatures and higher humidity levels than would otherwise be expected at lower elevations. Due to the combined effect of elevation and aspect, a differential melting process causes the snow cover to linger significantly longer on cool facing slopes, shaded valley bottoms, and at high elevations. This process affects the availability of fuels to burn, notably during the spring and fall months. Fire history research has shown that south facing slopes at low elevations can burn twice as frequently as high and cool facing slopes (Rogeau and Armstrong 2017).

The mountains are subjected to prevailing westerly winds. However, as winds drop into mountain valleys, wind flow patterns and speed become regulated by valley orientation and valley width. Upslope winds also occur by mid-afternoon as the warm air pooling at valley bottom starts rising upslope and shifts towards valley headwaters. Wind exposed slopes, which also tend to coincide with west facing slopes, desiccate much more rapidly. Local valley winds play an important role on fire behavior and the spread of wildfires in the mountains (Werth et al. 2011).

Table 3. Mean Annual Temperature (MAT, °C), Mean Temperature for the warmest (MTWM) and coldest month (MTCM). Mean frost-free period (MFFP, days) and Mean Annual precipitation (MAP, mm).

Natural Subregions	Area (km^2)	Mean temperatures (°C)	MFFP (days)	MAP (mm)
Banff				
Lower Foothills	In buffer only	1.8 (-12.8 to 14.7)	94	588
Upper Foothills	19 (0.2%)	1.3 (-11.6 to 13.4)	79	632
Montane	440 (4.5%)	2.3 (-10.0 to 13.9)	64	589
Subalpine	2,362 (24.3%)	-0.1 (-11.7 to 11.3)	55	755
Alpine	4,026 (41.3%)	-2.4 (-12.6 to 8.7)	40	989
Yoho & Kootenay				
IDF	5 (0.1%)	4.2 (-8.0 to 16.5)		530
MS	673 (6.9%)	2.5 (-10.0 to 14.5)		725
ESSF, IMA, ICH	2,212 (22.7%)	0.9 (-10.0 to 12.5)		925
Jasper				
Lower Foothills	In buffer only	1.8 (-12.8 to 14.7)	94	588
Upper Foothills	9 (0.1%)	1.3 (-11.6 to 13.4)	79	632
Montane	892 (7.9%)	2.3 (-10.0 to 13.9)	64	589
Subalpine	5,104 (45.5%)	-0.1 (-11.7 to 11.3)	55	755
Alpine	5,218 (46.5%)	-2.4 (-12.6 to 8.7)	40	989

Fire regime description

Fire cause, size, frequency, intensity, severity, and seasonality are attributes characterizing the fire regime of a region (Merrill and Alexander 1987), and variations between fire regimes are closely tied to natural subregions, or ecoregions (Arno 1980, Rollins et al. 2002). These biophysical units are defined in part by their topography, vegetation, and climate, which also represent the three components of the fire environment triangle (topography, fuel, weather) (Countryman 1972).

The forest mosaic of the southern Canadian Rockies has been shaped by wildfires for thousands of years. Beierle and Smith (1988) collected core sediments from multiple lakes located in the Montane, Subalpine and Foothills Natural Subregions of Banff National Park and Alberta Kananaskis Country and concluded the early Holocene climate was arid with much drier and warmer conditions than the present day. They also concluded Subalpine glaciers had completely receded by 9180 years BP. Most paleoecological studies of southern Alberta (Vance et al. 1983, Beirle and Schmitte 1988, MacDonald 1989, Schweger and Hickman 1989, Campbell et al. 2000) show constant and significant amounts of charcoal up until present, along with fire related species. Of particular interest to the Montane of BNP, a thick layer of charcoal embedded in the sediments of Johnson Lake, suggests a fire frequency so high it would have

completely denuded the landscape around 6800 years BP. In the subalpine of KNP, results from a paleo macro-charcoal fire history study obtained from Dog Lake revealed a steady mean fire return interval (MFRI) of 46 ± 5 years for the last 1000 years (Hallet et al. 2003). According to Schweger and Hickman (1989), the climate has been similar for the last 5000 years based on the consistencies of pollen counts, from which we can assume burning conditions to have been relatively similar as well.

Numerous tree-ring based fire history studies have been conducted in the Montane and Subalpine regions within and around the mountain parks since the 1970s (Hawkes 1980, White 1985a, 1985b, Masters 1990, Johnson and Larsen 1991, Rogeau 1994a, 1994b, Rogeau and Gilbride 1994, Rogeau 1996, Rogeau 1999, Rogeau 2010, Kubian 2013). These studies captured the rate of fire occurrence and burning between ca. 1600 -1950 by providing either MFRI or fire cycle (FC) values, which inform us on the expected average time between fires on the landscape, or the number of years required to burn an area equivalent to the total size of the forested landscape. Table 4 presents MFRI and FC values for the mountain parks region obtained from various methods of analysis, as well as different temporal scales, or spatial partitioning (i.e., by ecoregion or by topographic component such as elevation, aspect, valley orientation and proximity to the Continental Divide).

Table 4. Fire rotation periods expressed as fire cycle (FC) or mean-fire-return-interval (MFRI) values from fire history studies of mountain landscapes in southern Alberta - south of the Brazeau River. Adapted from Rogeau et al. (2016).

Location / Reference	Natural Subregion	Fire cycle or MFRI (yrs)	Method
Banff National Park (Van Wagner *et al.* 2006)	Montane and Subalpine	1285-1760 AD: FC = 58 - 76 1761-1940: FC = 105 - 182	Calculated from a Time-Since-Fire map. Variation by temporal period is from using four different methods of fire cycle calculation on the age-class distribution.
Banff National Park (Rogeau *et al.* 2004)	Subalpine	FC = 65 - 220	Calculated from weighted mean ages using a Time-Since-Fire map. Variation is by topographic location.
	Montane	FC = 44 - 145	
Castle Watershed (Rogeau 2012)	Subalpine	MFRI = 36 - 62	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
	Montane	MFRI = 19 - 31	
Elbow Watershed (Rogeau 2011a)	Subalpine	MFRI: 58 - 133	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
	Montane	MFRI: 32 - 70	
Kananaskis Valley (Johnson and Larsen 1991)	Subalpine	FC: 90	Calculated from a Weibull model applied to an age-class distribution derived from a Time-Since-Fire map.
N. Sask., Whitegoat & Siffleur Wilderness Areas (Rogeau 1999)	Subalpine	FC = 103 - 244	Calculated from weighted mean ages using a Time-Since-Fire map. Variation is by topographic location.
	Montane	FC = 71 – 82	
Peter Lougheed P.P. (Hawkes 1980)	Subalpine	MFRI = 101 - 304	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by topographic location.
Porcupine Hills (Rogeau 2014)	Montane	MFRI = 16 - 22	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
R11 FMU (Rogeau 2010)	Subalpine	Blackstone: MFRI = 54 - 84 Clearwater: MFRI = 57 - 59	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
	Montane	N. Sask: MFRI = 22 - 34 Red Deer: MFRI = 61	

Location / Reference	Natural Subregion	Fire cycle or MFRI (yrs)	Method
	Upper Foothills	Lower Ram: MFRI = 39 - 71	
Spray Lake Sawmills FMA: (Rogeau 2005, 2006, 2011b)	Subalpine	Highwood: MFRI = 59 Elbow: MFRI = 87	Calculated from a compilation of fire intervals obtained at fire history sampling sites.
	Montane	Highwood: MFRI = 27 Ghost: MFRI = 30 East Slopes: MFRI = 44	
	Upper Foothills	MFRI = 50	
Waterton Lakes National Park (Barrett 1996)	Lower Subalpine	dry aspect MFRI = 36 moist aspect MFRI = 55	Calculated from a compilation of fire intervals obtained at fire history sampling sites.
	Upper Subalpine	spruce-fir MFRI = 200 alpine larch MFRI = 64	
	Montane	low severity MFRI = 32 high intensity MFRI = 52	

Recent annual area burned values for the southern Rockies region of Alberta range from between .0075% (Stockdale et al. 2019a) to 0.25% (Rogeau 2005), which is well below the pre-European settlement period burn rate ranging from 0.7%-6% annually (varying by natural subregion; Hawkes 1979, Arno 1980, Barrett 1996, Rogeau 2005). The range in sizes of fires is broad with 97% of the area burned occurring in a few large fires (Stocks et al. 2002; de Groot et al. 2013). This dramatic reduction in annual area burned has changed the vegetation composition of the landscape considerably, with far less open canopy forest and grassland than there was more than 100 years ago (Rhemtulla et al. 2002; Fortin et al. 2018; Stockdale et al. 2019a) which has significantly raised the landscape likelihood of burning at high intensity (Stockdale et al. 2019b). While the landscape is adapted to wildfire as an ecological disturbance, there is increasing evidence that the trends in wildfire sizes and severity are increasing (Bergeron et al. 2001; Kasischke and Turetsky 2006; Giglio et al. 2010; Wang et al. 2017; Prichard et al. 2018). Shifts in fire regimes can have cascading effects that ultimately can result in entire ecosystems shifting into potentially novel configurations (Flatley and Fulé 2016). While Parks Canada's primary mandate is to preserve ecological integrity, this does not simply

imply allowing all fires to burn; Parks Canada has established different fire management zones that range from full suppression for public safety to zones where fire is allowed to play its natural role in the ecosystem. Large fires can burn tens of thousands of hectares in a matter of days and can threaten human lives and values when they burn into populated regions, as evidenced by the large fire that swept through Waterton Lakes National Park (WLNP) in 2017, forcing the evacuation of the Waterton Townsite.

Using BNP as an example, the historical mean fire size pre-dating 1940 was estimated at 1900 ha when considering only fires larger than 200 ha (Rogeau 1996). Since rocky ridges heavily dissect Subalpine forests, fire spread is limited in rugged mountain environments. As such, the maximum fire size was estimated at 10,000 ha. Based on values from Table 4 for BNP, the historical annual area burned in the Montane ranged from 140 to 460 ha based on an annual rate of disturbance ranging from 0.7% to 2.27%. In the Subalpine, the annual rate of disturbance ranged from 0.45% to 1.53%, which corresponds to an annual area burned ranging from 1,650 to 5,600 ha.

One reason why the rate of forest disturbance varies broadly across the landscape is due in part to the effect of topography and to variable exposure to sources of ignitions. It was found the spatial variation in fire occurrence in the mountains is significantly associated with elevation and aspect. Warm facing slopes at lower elevations burn twice as frequently as cooler aspects located at high elevations (Rogeau and Armstrong 2017). In that regard, being at low elevations, the Montane tends to be subjected to much shorter MFRIs than the Subalpine. In part because of its more clement weather conditions and longer snow-free period (i.e., longer fire season), but also in part because these low elevation valleys have always been preferred travel corridors by Indigenous peoples, early European settlers, and contemporary land users alike. Montane valleys contain main transportation corridors (highways, major roads, and railways) and human infrastructure and as such, and with this area experiencing higher fire frequency, this infrastructure is exposed to more fire risk.

As mentioned above, the source of fire (fire cause) is also an important fire regime regulator in dictating how frequently a watershed will burn. There is a clear distinction between the landscapes west and east of the Continental Divide, as well as between the Montane and

the Subalpine. Lightning strikes are not distributed evenly in time and in space, thus the risk of lightning fire is not equal across all mountain parks (Weirzchowski et al. 2002). There is a documented lightning strike shadow over most of the mountain parks where very few strikes (less than 10 per 25 km^2 on the east side of the Divide – unpublished Alberta lightning data 2006 – 2015; less than 50 strikes per 25 km^2 1989-1994 (Wierzchowski et al. 2002). However, the spatial distribution of lightning strikes shows an increased number of strikes for the south-eastern end of BNP and for most of KNP. A salient finding of Wierzchowski et al. (2002) was the lightning strike effectiveness in starting forest fires between British Columbia and Alberta is vastly different. In BC, it only takes 50 strikes to start a fire, whereas it takes 1400 to start a fire in AB. Not all controlling agents of lightning fire occurrence are well understood, but elevation, average fuel severity rating and vegetation composition were recognized as lead factors. However, for Alberta it is believed that a large random component exists between lightning strike density and fire occurrence (Wierzchowski et al. 2002). The proportion of lightning fires, in contrast to human-caused fires, east of the Divide is 25% in the Subalpine and only 10% in the Montane. West of the Continental Divide, lightning is the prevailing source of fire ignitions for both the Montane and Subalpine, but the Montane remains at an elevated fire risk due to the volume of recreational land users at valley bottom.

Historically, the Montane was characterized by a mixed-severity fire regime driven by regular fire occurrence with variable burn intensities that resulted in an intricate mosaic of partially burned and fully burned patches of forest. In contrast, lower fire frequencies and longer intervals between forest fires, common to the Subalpine environment, produced more intense fires where few patches of trees survived (island remnants) within burn perimeters. As a result of aggressive fire suppression and fire exclusion policies, the amount of area burned by wildfire has dropped drastically since the 1940s in the mountain parks and elsewhere in North America (Keane et al. 2002). Many studies have documented a significant departure in fire regime conditions for the Montane region of Alberta (Rhemtulla et al. 2002; Rogeau et al. 2016; Chavardez and Daniels 2016) and British Columbia (Marcoux et al. 2015) where it is expected that future Montane fires will be greater in intensity and severity and reminiscent of Subalpine fires. To date, studies from Subalpine environments have not found current fire regime

conditions to have significantly departed from historical ones (Sherriff et al. 2001; Sibold et al. 2006; Rogeau 2016) with the exception that fire severity and fire size appear to be increasing (Stephens et al. 2014; Schwartz et al. 2015).

Recreation description

These iconic national parks attract millions of tourists who flock each year to the Canadian Rockies. Banff National Park has the highest visitation rates (Table 1) of all national parks, park reserves and marine conservation areas in Canada. Visitation rates within all the Rocky Mountain parks (Banff, Jasper, Kootenay, Yoho) has increased yearly. The core of the visitation use remains along the main travel corridors of the parks such as the Trans-Canada Highway that traverses both Yoho and Banff National Parks, the Bow Valley Parkway in BNP, the Icefield Parkway (Highway 93 North) that connects Banff and Jasper, and Highway 93 South that crosses Kootenay National Park in its entirety. Many visitors come with their own vehicles, but there is a large component of bus tour companies that bring tourists from around the world. Most infrastructure, such as lodging, restaurants, gift shops and other amenities, are largely located in the Town of Banff, as well as in the Hamlet of Lake Louise and the small community of Field in Yoho National Park. Some seasonal and year-round lodging and dining facilities are found along the main travel arteries within the mountain parks, as well as at Lake O'Hara and Emerald Lake within YNP. Along the main service roads and core areas, are several fully serviced RV and tent campgrounds. For backcountry enthusiasts, there is an extensive network of hiking trails with camping shelters or primitive camping facilities, as well as ten Alpine Club of Canada huts, and a handful of catered backcountry lodges. During the summer months, trails within 20 km of trailheads experience high traffic from day hikers. Banff National Park also includes three ski resorts: Sunshine Village, Lake Louise, and Mount Norquay, which all offer summer activities. Sulphur Mountain Gondola located on the outskirt of the Town of Banff has interpretive and dining facilities on top of the mountain and attracts thousands of visitors daily. Day and multi-day backcountry horseback riding trips are also popular in various regions of BNP.

On any given summer day, thousands of people are dispersed in proximity to parks' facilities and road access, and hundreds more can be found in remote, backcountry areas of the parks. During high fire hazard days, should a wildfire breakout, fire management can become

problematic due to the high volume of visitors, as well as the vast extent and remoteness of some regions.

Numerous townsites of significant population density are found along the TransCanada highway that traverses the park. Many hotels, campgrounds, and other city amenities can be found in Canmore, Banff, Lake Louise, and Field.

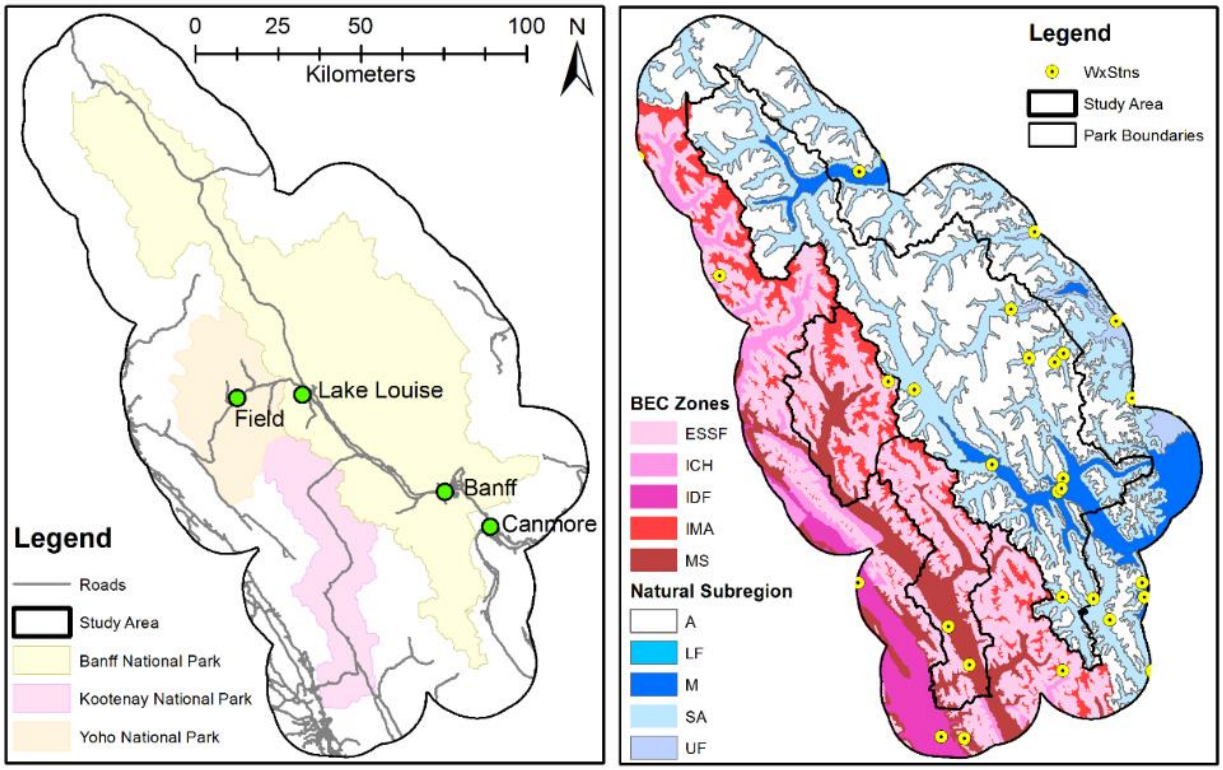

Figure 2. (LEFT) Location of townsites (green dots) within Banff, Kootenay and Yoho National Parks as well as main roads and the extent of the study area. (RIGHT) Location of the weather stations (WxStns) within the study area as well as the Biogeoclimatic Ecosystem Classification (BEC) zones and Alberta Natural Subregions. BEC zones are: Engelmann Spruce – Supalpine Fir (ESSF), Interior Cedar – Hemlock (ICH), Interior Douglas-Fir (IDF), Interior Mountain-heather/alpine (IMA) and Montane Spruce (MS). Alberta Natural Subregions are: Alpine (A), Lower Foothills (LF), Montane (M), Subalpine (SA), and Upper Foothills (UF).

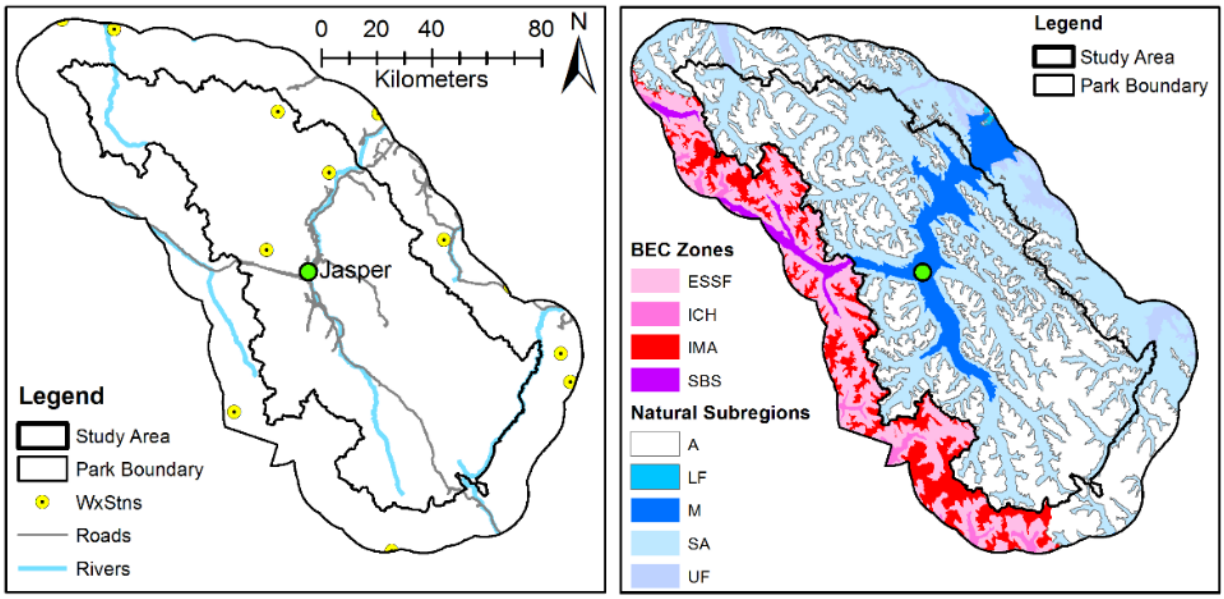

Figure 3. (LEFT) Location of the town of Jasper (green dots) within Jasper National Park as well as main roads, weather stations and the extent of the study area. (RIGHT) The Biogeoclimatic Ecosystem Classification (BEC) zones on the side of British Columbia and Alberta's Natural Subregions. BEC zones are: Engelmann Spruce – Supalpine Fir (ESSF), Interior Cedar – Hemlock (ICH), Interior Mountain-heather/alpine (IMA) and Montane Spruce (MS). Alberta Natural Subregions are: Alpine (A), Lower Foothills (LF), Montane (M), Subalpine (SA), and Upper Foothills (UF).

Waterton Lakes National Park

General description

Waterton Lakes National Park is the smallest and southernmost (505 km^2) of the Alberta Rocky Mountain Parks (Figure 1 and Figure 4) and was established in 1895. It borders Montana's Glacier National Park (USA), and in 1932, Waterton Lakes and Glacier National Parks were "merged" to become the world's first International Peace Park. In 1995 the Peace Park was also designated a UNESCO World Heritage Site. The geography of WLNP is highly variable with a very sharp gradient between the prairies to the east, and steep rugged mountains to the west. The foothills and parkland in the eastern portion of the park are home to a small herd of grazing bison (*Bison bison*), and immediately outside the park lie open prairie, ranchlands, and expansive agricultural lands. The mountains of the park are rugged, and the tallest peak of Mount Blakiston rises some 1600m above the immediately adjacent prairie landscape. Immediately north of WLNP is a large newly created provincial park, the Castle-Crown Wilderness, as well as commercial forest holdings. The western boundary of WLNP is the Continental Divide, and west of the Divide lie commercial forest lands in British Columbia. Within the park itself, there are beautiful mountainous landscapes and crystal-clear lakes.

Waterton has some of the richest biodiversity in Alberta and is home to many vertebrates (60 spp. mammals, 250 spp. birds, 24 spp. fish and 10 spp. reptiles). Large predatory species include the grizzly bear (*Ursus arctos*), black bears (*U. americanus*), wolves (*Canis lupus*), coyotes (*C. latrans*) and cougars (*Puma concolor*). Native foothills fescue grasslands and endangered white bark and limber pine are protected within the borders of the park.

The park contains the townsite of Waterton, which is home to a small number of permanent year-round residents (less than 100), but in active tourism months of May through September, contains many thousands of visitors staying in several hotels. Thousands of day-visits occur from the surrounding communities. In September of 2017, a wildfire started on Mt Kenow in British Columbia, and burned into the Waterton consuming over 19,000 ha, which was approximately 39% of the park's area. Large areas of the park remain closed to the public as the ecosystem continues to regenerate post-fire.

Vegetation description

Like Banff and Jasper National Parks, Waterton Lakes National Park is within the Canadian Rockies and has varied vegetation associated with the elevation-dependent Alberta Natural Subregions (Table 5). WLNP has one Natural Subregion (Foothills Parkland) that is unique compared to the mountain parks to the north. The rolling hills of the Foothills Parkland are dominated by fescue interspersed with copses of aspen and willow. After the 2017 Kenow fire, many of the areas which experienced severe burning remain blackened at the surface while in other areas grasses have begun regenerating.

The other Natural Subregions within WLNP are largely the same as can be found in Banff, Yoho, Kootenay, and Jasper to the north, with most of the following information repeated from the BYKJ section. Lodgepole pine is the dominant species and can be found at all elevations and notably on warmer facing slopes. Both aspen and Douglas-fir are constrained to the Montane. Douglas-fir trees tend to establish on xeric sites. In contrast, spruce stands are normally found on cooler aspects and at valley bottom where soils are more mesic. White spruce trees prevail in the Montane, while Engelmann spruce and subalpine-fir trees are commonly found together in the Subalpine. Scattered alpine larches, as well as limber and whitebark pines, commonly grow near treeline. Apart from spruce and fir trees, all tree species are fire-adapted and have coping mechanisms to survive light surface fires to intense stand-replacing fires.

Within the forested area, shrubby and grassy meadows are common and largely occur along flat valley bottoms and low angled slopes. The ruggedness of the landscape and steep angled slopes produce avalanche paths vegetated by shrubs, forbs, and grasses, which dissect the forest cover and can affect fire behavior and the rate of fire spread. Above treeline, extensive alpine meadows exist largely as heath tundra. Most meadows do not have enough continuous cover of tall grasses or forbs to sustain wildfire spread over mountain passes or some significant distances into nearby forests.

Climate description

Cooler wetter conditions can be found at higher elevation in the Mountains with increasing temperatures at lower elevations. This park also shows a longitudinal gradient, temperatures are cooler to the west of the park near the continental divide and warmer on the east

bordering and within the Foothills Parkland. The Parkland is still characterized with cooler summer and shorter growing seasons, but considerably warmer winter conditions than the open prairie grasslands. According to the Köppen Climate Classification system, WLNP shares climatic conditions with the southern end of Banff National Park and is in the humid continental climate (Dfb) with mild summers and wet all year. The Continental Divide strongly affects the amount of precipitation received. On the lee side (east) of the Divide far less precipitation falls than the west slopes, which are subjected to moist Pacific air masses that deposit large amounts of precipitation (rain or snow) due to the orographic effect of the mountains. Some general climate information for the WLNP is shown in Table 5.

Regardless of its position relative to the Continental Divide, topography affects temperatures, relative humidity, and precipitation (Janz and Storr 1977). Shadows from mountains and ridges maintain lower temperature and higher humidity than would be expected at lower elevations. Elevation and aspect combine to create differential melting rates which causes snow to linger significantly longer on cool aspects, shaded areas, and high elevations. This process affects the availability of fuels to burn, notably during the spring and fall months. Fire history research has shown that south facing slopes at low elevations can burn twice as frequently as high and cool facing slopes (Rogeau and Armstrong 2017).

The mountains are subjected to prevailing westerly winds. However, as winds drop into mountain valleys, wind flow patterns and speed become regulated by valley orientation and valley width. Upslope winds also occur by mid-afternoon as the warm air pooling at valley bottom starts rising upslope and shifts towards valley headwaters. Wind exposed slopes and outflow areas dry more rapidly. Local valley winds play an important role on fire behavior and the spread of wildfires in the mountains (Werth et al. 2011). Waterton is one of Alberta's windiest places, winds over 100km/h are not uncommon. Chinook winds (a type of foehn wind) contribute to keeping winter temperatures relatively warm.

Table 5. Mean Annual Temperature (MAT, °C), Mean Temperature for the warmest (MRWM) and coldest month (MTCM). Mean frost-free period (MFFP, days) and Mean Annual precipitation (MAP, mm).

Natural Subregions	Area (km^2)	Mean temperatures (°C)	MFFP (days)	MAP (mm)
Foothills Parkland	40 (8.0%)	3.0 (-9.6 to 14.7)	76	517
Montane	138 (27.8%)	2.3 (-10.0 to 13.9)	64	589
Subalpine	258 (51.9%)	-0.1 (-11.7 to 11.3)	55	755
Alpine	61 (12.3%)	-2.4 (-12.6 to 8.7)	40	989

Recreation description

Waterton Lakes National Park experienced an intense fire in September of 2017, and most of the backcountry in the west of the park was closed until the summer of 2019, when it has since been reopened. The town site as well as other hiking trails on the east of the park remain accessible. Waterton Lakes National Park offers hiking and trails of various skill levels (200km), beautiful sights of waterfalls and lakes accessible by car, and a stunning lakeside town to relax and enjoy. The park has two designated National Historic Sites (NHS): The Prince of Wales Hotel NHS; and the First Oil Well in Western Canada NHS. Waterton is designated as a Dark Sky preserve.

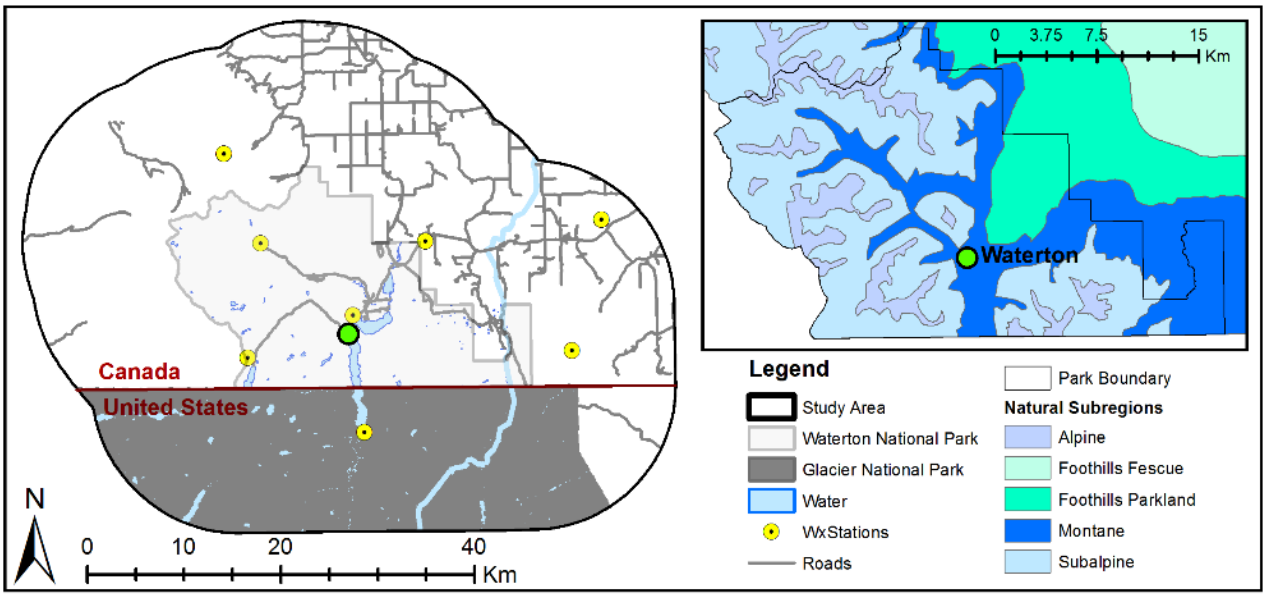

Figure 4. Location of the weather stations, roads, and the townsite (green dot) within Waterton Lakes National Park study area, including the Alberta Natural Subregions (inset): Alpine (A), Lower Foothills (LF), Montane (M), Subalpine (SA), and Upper Foothills (UF).

Riding Mountain National Park

General description

Riding Mountain National Park (RMNP) is in Manitoba (see Figure 1 and Figure 5) and was established in 1929 as a 2,969 km^2 National Park, and in 1986 it was designated a biosphere reserve by UNESCO. The northeastern part of the park borders the Manitoba escarpment while the rest of the park is surrounded by farmlands. The town site of Wasagaming is located on the south shore of Clear Lake. During the summer, the town is home to approximately 40,000 cottagers.

The park encompasses three distinct ecosystems: grasslands, upland boreal and eastern deciduous forests. The mosaic of wetlands and upland forests produces considerable biodiversity, including large mammals such as wolves, elk (*Cervus canadensis*), bears and bison. RMNP is home to various species of birds, which include trumpeter swans (*Cygnus buccinator*), golden-winged warblers (*Vermivora chrysoptera*), red-headed woodpeckers (*Melanerpes erythrocephalus*), chimney swifts (*Chaetura pelagica*), and Canada warblers (*Cardellina canadensis*), and bats such as the little brown bat *(Myotis lucifugus*), and long-eared myotis (*M.*

evotis), the northern leopard frog (*Lithobates pipiens*), the monarch butterfly (*Danaus plexippus*) and the tiger salamander *(Ambystoma tigrinum*).

Vegetation description

Riding Mountain National Park is located at the convergence of grasslands, upland boreal and eastern deciduous forests, atop the Manitoba escarpment. The landscape is characterized by a mosaic of deciduous/mixedwood forests interspersed with wetlands. The park grasslands consist of shrublands, low shrubland, and wetlands. Forested areas consist of dominant aspen parkland, eastern deciduous forest, and mixed canopy coniferous forests.

Aspen parkland is a tall-canopy deciduous forest with an herb-rich understory dominated by stands of pure trembling aspen on nutrient-rich sites, or mixed eastern deciduous forest. The tree species associated with the mixed eastern deciduous forest type include green ash (*Fraxinus pennsylvanica*), America elm (*Ulnus americana*), Manitoba maple (*Acer negundo*), paper birch, and cottonwood, with minor components of balsam poplar. Deciduous forested areas are alternating with shrubby grasslands, forming a complex mosaic pattern at the landscape level. Balsam poplar stands and small wetlands occur in poorly drained areas. Tall shrubs (beaked hazel (*Corylus cornuta*), and red-osier dogwood (*Cornus sericea*)) are frequent. Rich and varied forb-dominated understory.

Conifer-dominated stands includes semi-treed bogs and fens (black spruce and/or larch), and sparsely treed dry uplands (white spruce). Mature, regenerating stands dominated by coniferous trees, generally pure stands of white spruce, black spruce, or balsam fir. Deciduous tree species may form a minor component. Feathermosses may dominate the understory. Mixed canopy forests, typically with trembling aspen and white spruce as codominants; black spruce, paper birch, balsam poplar and jack pine are occasional.

Vegetation outside the park is variable, mostly remnant groves of trembling aspen and/or balsam poplar in agricultural areas. Green ash and Manitoba maple occur along watercourses. Mature and regenerating coniferous and deciduous forests are found in the Duck Mountains.

Climate description

RMNP has hot continental summers and cold winters. Most of the rainfall occurs from April to October, with June being the wettest month. In winter months snowfall can be variable across the different elevations in the park. 30-year climate normals (1981-2010) for the town site of Wasagaming indicate a monthly average precipitation ranging from 15.7 to 80.1mm and a mean total of 488mm. The area experiences high relative humidity due the numerous lakes and wetlands in the region. Daily mean annual temperature for the town site is 0.7°C.

Recreation description

Many trails for hiking and lakes for water activities such as boating, sailing, fishing, and swimming at the beach. Near to the town site camping, picnicking and golf are all available. Designated as a Dark Sky reserve Riding Mountain National Park is the place to be to watch the northern lights dance the night away.

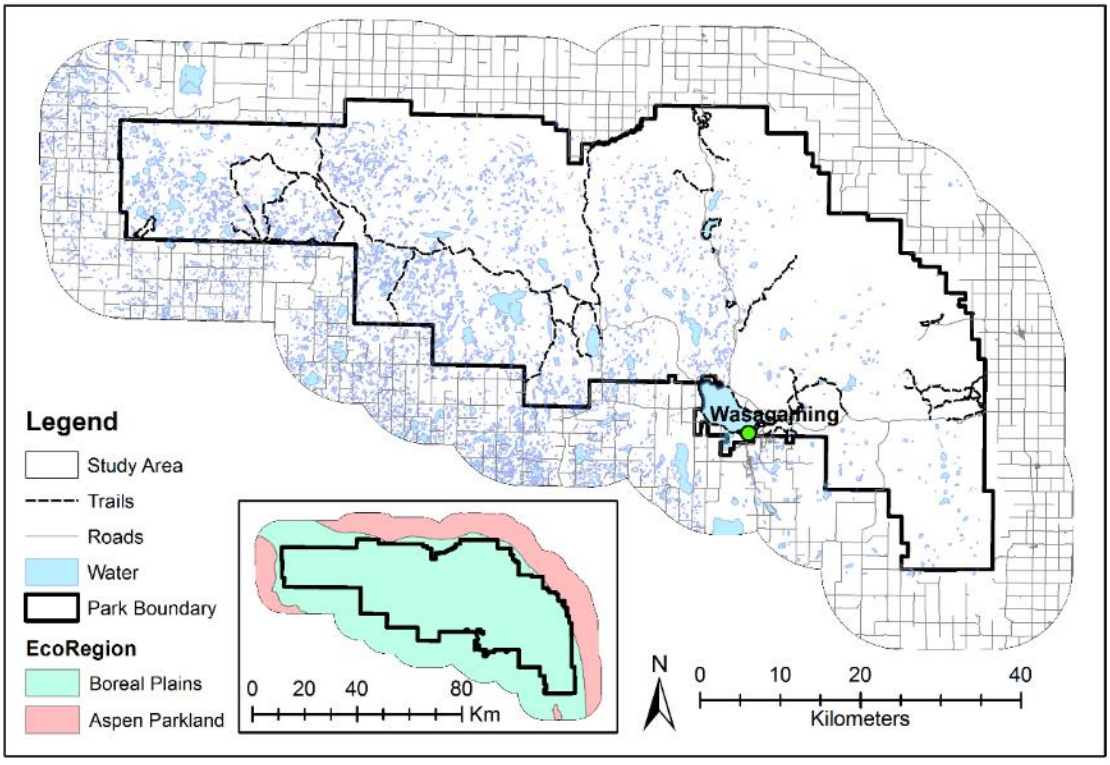

Figure 5. Location of the town of Wasagaming and the roads within Riding Mountain National Park and surrounding study area as well as the local ecoregions of Boreal plains.

3. Methods

Burn-P3 Modelling

We used the Burn-P3 model (Parisien et al. 2005) to generate a wide array of data, including raster outputs such as burn counts and probabilities, fire intensity, crown fraction burned, as well as shapefiles of fire origin points and fire perimeters over the four modeling domains. For the BYK landscape, we conducted more detailed analyses to assess the efficacy of fuel treatment scenarios, and examined fire source and sink dynamics (Parisien et al. 2019). Burn-P3 is a Monte Carlo simulation model and uses the Prometheus fire growth engine to simulate ignition and spread of fires across the landscape. Burn-P3 starts fires in locations based on a user-defined spatial layer to describe the likelihood of a fire starting at a given point on the landscape. Fires are then grown using weather conditions based on user-defined parameters (that are often derived from historical weather, but this is not a strict requirement). To conduct this analysis, we needed a current and accurate fuel map, a detailed digital elevation model, weather data, and an understanding of the locations and probabilities of fire ignitions. Fuels are represented by Fire Behaviour Prediction System (FBP) (Forestry Canada Fire Danger Group 1992) fuel types. Burn-P3 accounts for changes in some key plant phenology attributes such as broadleaf deciduous leaf-presence or -absence, and the degree to which grass is cured (dead and brown). These phenological attributes are used as proxies to examine the effect of seasonal changes on fire behaviour, by triggering leaf-off or leaf-on for deciduous or mixed-wood fuel types (D1/M1 or D2/M2 respectively), and degree of grass curing. Seasonal changes are also controlled by weather inputs being used from the appropriate season being modeled. Topography, the third element of the fire behaviour triangle (fuels – weather – topography), is derived from the input DEM.

Each Burn-P3 model run (hereafter “iteration”) simulated a single wildfire, and we ran between 100,000 and 1,250,000 Burn-P3 iterations per model domain. Model outputs that we used consisted of the burn probability (hereafter “BP”), mean fire intensity (kW/m^2) and simulated fire perimeters. The following sections detail the Burn-P3 data inputs and model-building process. Each modeling domain required different approaches due to idiosyncrasies in

the data that was available. These four domains are all described in their own sections below. Preparation of inputs for running the Burn-P3 model involves compiling and creating numerous data inputs related to the vegetation, weather, and fire history of the modeling domains (Table 6). The general approaches to how model inputs were created are described in the table and below. For specifics of each modeling domain, however, refer to the methods sections for each of the domains.

Table 6. Static and stochastic inputs used to model burn probability.

Model Input	Data Type	Description
Static inputs:		
Fuels	Categorical raster	Canadian Forest Fire Behavior Prediction System fuel type classifications and non-fuel features derived from various data sources. See individual model domain sections in the report for specifics on each domain.
Topography	Continuous raster	Elevation data supplied by various data repositories at 100m resolution.
Fire zone	Categorical raster	For some of the modeling domains we defined specific fire zones (BYK, Jasper), whereas for others we did not distinguish fire zones due to the smaller size of the landscape (WLNP, RMNP).
Seasons	Setting	Start and stop dates for fire weather, grass curing, and deciduous green-up change:
Stochastic inputs:		
Number of fires	Frequency distribution	Only one fire was burned in every iteration of the model runs for all modeling domains.
Escaped fire rates	Frequency distribution	Proportion (%) of fires ≥ 3 ha occurring in each combination of season, cause (human, lightning), and fire zone.
Spread days	Frequency distribution	Number of days a fire is expected to spread. This was derived in different ways for each modeling domain due to available data.
Spread hours	Frequency distribution	The number of hours per day a fire is expected to spread. Burning hours were set at 1/3 of available daylight hours per season.
Ignition locations	Continuous raster	Relative probability surface of human and lightning ignition locations is based on 1961-2018 fire history records and the model assigned ignitions based on these probabilities. Ignition location surfaces were developed using a variety of machine learning algorithms in R.
Daily fire weather	Numeric list	Daily weather conditions observed at noon MST and associated Canadian Fire Weather Index System codes and indices partitioned by season and fire zone. Weather observations from appropriate stations with ≥ 20 years of historical records were used.

Fuels

Fire modelling requires that vegetation cover for the study area be classified and converted to fuel types, as described by the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Hirsch 1996). A fuel type is defined as "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behaviour under defined burning conditions" (Merrill and Alexander 1987). Fuel characteristics are an important determinant of fire behaviour, including rate of spread, fuel consumption, fire intensity, and fire growth for 16 benchmark fuel types. Fuel types are grouped into five major fuel type groups: coniferous, deciduous, mixedwood, slash, and open grass.

The fuel grids used for all modeling domains were at a spatial resolution of 100m, and the data sources and methods used to create each domain's fuel grid is described in detail within the methods sections for each domain. Data sources for fuel information included: a) the annually updated fuel grid supplied by the Government of Alberta Forest Protection Branch; b) a national scale fuel grid (Government of Canada (GOC) fuel grid) developed from remotely sensed vegetation data collected and evaluated by Beaudoin et al. (2014); c) vegetation cover maps derived from a recent Vegetation Resources Inventory assessment conducted for Banff National Park; d) vegetation cover maps developed for Waterton Lakes National Park by the US Parks Service for Glacier National Park (and extended north to Waterton Lakes); e) vegetation cover maps for Riding Mountain National Park; f) Ecological Land Classification (ELC) data developed in 1990. Each of the layers were combined in order to ensure the most accurate fuel grid was created for use in Burn-P3. The FBP fuel types present in the study areas are:

- C-1 (spruce lichen woodland)
- C-2 (boreal spruce)
- C-3 (mature lodgepole pine)
- C-4 (immature lodgepole pine)
- C-5 (red and white pine)
- C-6 (conifer plantation)
- C-7 (Ponderosa pine – Douglas-fir)
- D-1/D-2 (leafless/leafy aspen)
- M-1/M-2 (leafless/leafy mixedwood)
- M-3/M-4 (leafless/leafy dead balsam fir mixedwood)
- S-1 (jack pine slash)
- S-2 (spruce slash)
- O-1 (grass)

In cases where fires were known to have burned since the time of the fuel inventory provided, we used a transition matrix (see Table 7) to modify the fuel type in these burned areas. Note that this transition value for fuels-post-fire is not meant to represent what the actual vegetation is on the ground, but instead is meant to represent an appropriate fuel type would be that would give a realistic rate of spread based on the vegetation structure and composition. This conversion of vegetation into FBP fuel type was done based on expert opinions and following the conversion table in the British Columbia Wildfire Fuel Typing and Fuel Type Layer Description (Perrakis et al. 2017). Depending on the age of the spatial vegetation layer, most recent wildfires had to be included, and vegetation within a burned area was "aged" according to a defined state and transition model (Table 7).

Table 7. Fuel state and transition model for aging a landscape post-fire based on the original fuel type and time since fire (TSF).

	Original Fuel Type			
TSF (years)	Coniferous	Mixedwood	Deciduous	Grasses
0-5	M-1/M-2 05 PC	O-1	O-1	O-1
6-10	M-1/M-2 10 PC	D-1/D-2	D-1/D-2	
11-15	M-1/M-2 15 PC			
15-25	M-1/M-2 25 PC	M-1/M-2 05 PC		
25+	Returns to the original fuel type present			

There were cases where additional information from local staff was available and the state and transition model was not followed as laid out in Table 7. Site specific fuel modification will be further discussed in the area specific sections to follow.

Topography

Topography was represented by a Digital Elevation Model (DEM), which was derived from the Canadian Digital Elevation Model (CDEM). The DEM is then resampled to the same resolution as the fuels layer.

National Fire Database

The Canadian National Fire Database (CNFDB) is a federal database of forest fire records and includes records from provinces, territories, and Parks Canada (Natural Resources Canada 2020). The CNFDB database includes forest fire records from 1946 to the present, and is

updated annually (Figure 1, Figure 2, and Figure 3). We used records from the CNFDB to develop Burn-P3 inputs for ignition locations, seasonality, and cause. These parameters were based on fires occurring within the Rocky Mountains of Alberta and British Columbia since 1960. For Riding Mountain National Park, we used fires occurring in the Manitoba and Saskatchewan boreal forest over the same period and size thresholds.

Fire Zones

We mapped all known fires in the regions to determine if there were distinct patterns in cause, seasonality, and/or size of fires in different parts of the study area (Figure 6). Fires within the modeling domains area were grouped by their cause, and season. For each of the modeling domains we created distinct fire zones, and more detail is provided in the methods for these domains.

Weather Zones

Weather zones from the perspective of the Burn-P3 model are defined as areas of the landscape which have distinct spatial variability in weather patterns. Weather zones were determined based on Western North America 30-year (1961-1990) climate normals (Hamann et al. 2013) of mean annual temperature (MAT) and mean annual precipitation (MAP). For each of the modeling domains we created distinct weather zones when there was significant variation in in MAT and MAP across the landscape. Ecological classifications such as the Alberta Natural Subregions or the British Columbia biogeoclimatic ecological classification (BEC) zones can be used as proxies for weather zones as they are largely defined by climate and vegetation type. More detail is provided in the methods for these domains.

Seasons

Seasons were determined based on the number of historical fires as well as total area burned from the National Fire Database (NFDB). Historical fires were visually represented by Human and Lightning causes and season were determined based on changes throughout the year. We also examined known dates of deciduous green-up and grass curing stages to further refine seasonal definitions. These delineations of seasons were then approved by fire managers for individual parks. See summary tables for each National Park below.

Ignition Grids

Ignition grids were created using a machine-learning approach in R based on historical ignition points divided by cause (human or lightning). Machine-learning processes included Random Forest (R Package randomForest), and Boosted Regression Tree (R Package dismo) analyses (Liaw and Wiener 2002, Hijmans et al. 2020, Kuhn 2021). Variables used for lightning ignitions were elevation, TPI (topographic position index, which describes features such as steep slopes, benches, valley bottoms, plateaus etc.), TRI (terrain ruggedness index, a similar metric to TPI that demonstrates the difficulty for humans to traverse), historical lightning strike locations, and area solar radiation. Topographic indexes (TPI and TRI) were generated using the R Raster package (Hijmans, 2021). For human caused ignitions a road and trail density grid as well as distance to roads and trails raster was included in addition to elevation, TRI, and TPI.

Spread Days

Spread event day (SED, which is the number of days individual fires burn with significant increase in area) distributions were calculated from historical weather stations with the longest duration of records for each National Park. The SED distribution was determined differently for the various Parks to account for differing data availability. In Banff, Yoho, and Kootenay these were determined as a sequence of days with potential for intermittent crown fire, based on the initial spread index (ISI) and build up index (BUI) combinations which result in a crown fraction burned of greater than 50% in a C-3 fuel type. Additionally, Banff potential spread event days were limited to the number of days that a fire would reasonably persist on the landscape prior to substantial suppression activity. The upper limit on the spread event days was set to 5 after conversations with Banff staff. For the other modeling domains, we followed the approach in Parks (2014) which examines MODIS hotspots of historical large fires (>200ha) to determine the number of days of significant fire growth. These distributions are then calibrated in an iterative fashion to have the modeled fire size distribution approximate the historical fire size distribution. In the case of Jasper NP, we truncated this distribution to six days as the model kept over-burning the park with the settings derived from Parks' (2014) methods. See Table 8 for the SED for each modeling domain.

Table 8. Spread event day (SED) distribution for each of the modelled National Park domains, Banff, Yoho and Kootenay National Parks (BYK), Jasper National Park (JNP), Waterton Lakes National Park (WLNP) and Riding Mountain National Park (RMNP). Calculated from historical fire weather data as the number of consecutive days with potential of crown fire, depending on the initial spread indices (ISI) and build-up indices (BUI).

SED (days)	BYK (% fires)	JNP (% fires)	WLNP (% fires)	RMNP (% fires)
1	55.00	51.99	57.69	64.64
2	22.00	20.97	11.04	19.55
3	11.20	11.28	6.20	7.42
4	6.90	6.97	4.58	3.28
5	4.90	4.32	3.80	2.12
6	-	4.50	3.33	1.25
7	-	-	3.02	0.77
8	-	-	2.80	0.39
9	-	-	2.64	0.19
10	-	-	2.51	0.19
11	-	-	2.39	0.10
12	-	-	-	0.10

Fire Weather

Daily fire weather was extracted from the Meteorological Society of Canada (MSC) database. Weather stations within or very close to the modeling domains were examined to find ones with the relevant attributes of temperature, wind speed, wind direction, relative humidity, and precipitation. These weather attributes were converted to Fire Weather Index (FWI) values using the CFFDRS package in R.

Starting values for the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC) were calculated using adjacent weather stations where available. Normally, overwinter precipitation is used to define these starting indices, however that data is not available at all weather stations.

Other Inputs

To properly simulate fire behaviour in seasonally-variable fuel types such as grass and deciduous trees, which have distinct phases of green-up, senescence, and curing, key dates of vegetation change are required. For example, green-up dates, grass curing percentages by season, and grass fuel loads were determined based on a review of key literature, and

discussions with fire management representatives from each National Park. This approach was also used to determine the key dates for when aspen and poplar trees have their leaf-flush in the spring, and when their leaves fall off in the late summer or early autumn.

Wind direction is driven by topography, and in mountain environments, this can result in complex wind-fields across the landscape. To account for the effect of topography on wind speed and direction, we used WindNinja to create wind grids based on the 100m resolution DEM. WindNinja solved for conservation of mass and momentum at 30 km/h resulting in a spatial grid for each cardinal input wind direction and speed. Another input required by the Burn-P3 model that is required to control fire size in addition to the spread event day distribution is the hours of burning per day that is allowed by the model. We set the hours of burning to be equal to 1/3 of the available daylight hours (*Rogeau, personal communication*). Seasonal dates, hours of burning, percent curing, green-up dates, and proportion of ignitions by season and cause are given in Table 9.

Table 9. Variables included in the Burn-P3 model for the simulated national parks of Banff, Kootenay and Yoho (BYK), Jasper (JNP), Riding Mountain (RMNP), and Waterton Lakes National Park (WLNP). Variables included the median seasonal date, daily hours available for burning, percent curing of the grass fuel type (O-1), green-up day for deciduous aspen fuels (D-1/D-2), probability (%) of ignition in any given season by cause either human or lightning.

Season	Dates	Hrs burning	% Curing	Green-up	Ignitions Probability	
					Human	Lightning
BYK						
Early Spring	04/16	4.64	90	OFF	50.54	0.00
Late Spring	05/16	5.21	80	OFF	49.46	0.00
Early Summer	07/01	5.50	5	ON	29.14	22.26
Late Summer	08/16	4.83	65	ON	18.04	22.25
Early Fall	09/08	4.36	80	ON	6.17	0.00
Late Fall	09/22	4.05	100	ON	2.14	0.00
JNP						
Spring	04/30	5	75	OFF	15.12	2.33
Summer	07/07	6	25	ON	29.07	34.88
Fall	09/07	4	90	ON	17.44	1.16
WLNP						
Spring	04/23	4.75	90	OFF	10.99	1.10
Early Summer	06/15	5.42	10	ON	7.70	6.60
Late Summer	08/08	4.91	50	ON	13.19	41.76
Fall	09/16	4.17	100	ON	14.29	4.40
RMNP						
Spring	04/23	4.73	90	OFF	53.30	0.96
Summer	07/01	5.41	10	ON	20.95	4.76
Fall	09/08	4.35	100	ON	15.24	4.76

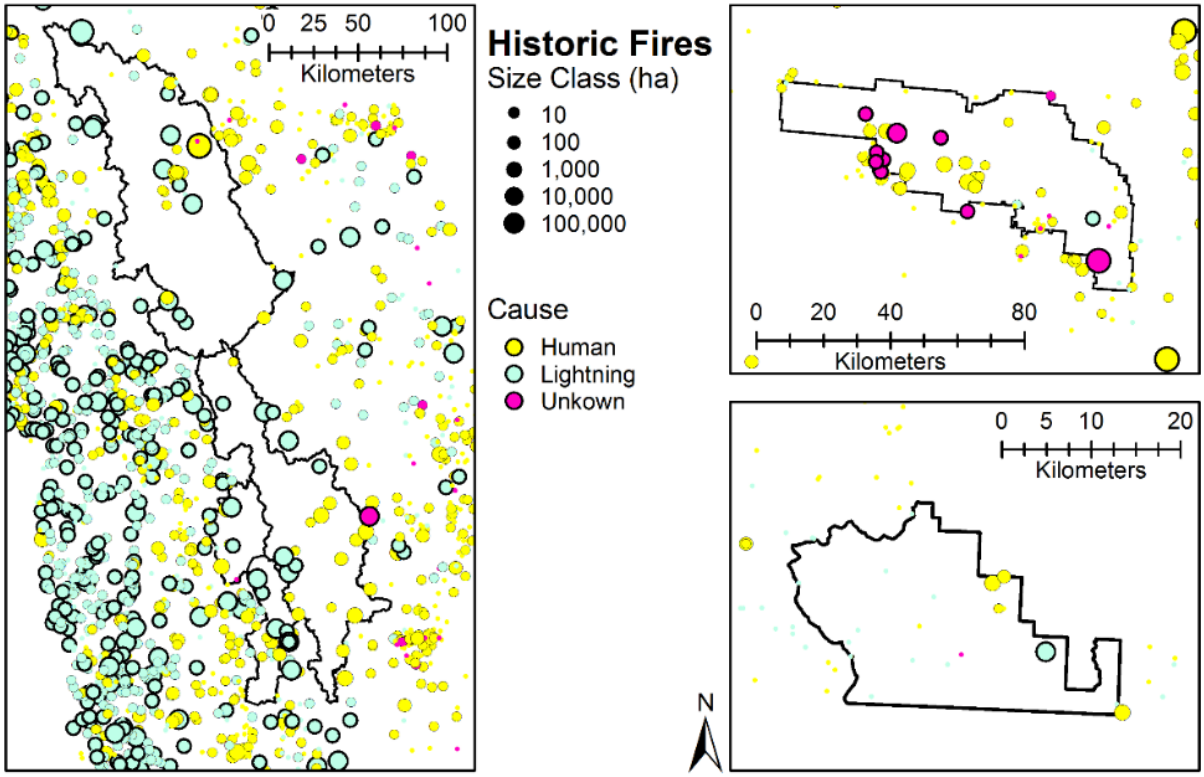

Figure 6. Location of all human and lightning caused fires by fire size across (LEFT) Banff, Jasper, Kootenay, and Yoho National Parks, as well as (RIGHT TOP) Riding Mountain National Park and (RIGHT BOTTOM) Waterton Lakes National Park.

Analysis Methods: Processing Burn-P3 Outputs and Map Development

While Burn-P3 can produce numerous outputs, we primarily used the burn probability and counts, fire perimeters, and fire intensity outputs for all the modeling domains. We then developed Relative Burn Likelihood maps which describes the ratio of the burn probability of a given cell relative the landscape-level mean probability where we compute the mean BP of the entire landscape. For example, if the mean burn probability of the landscape is 0.025, and two given locations have burn probabilities of 0.0125 or 0.05, the Relative Burn Likelihood values for those two locations are -2 (two times lower than the mean) and +2 (two times higher than the mean).

We created fire hazard maps for all modeling domains by partitioning BP into 4 equal classes (dividing the maximum BP of the landscape by 4) and partitioning fire intensity into four classes as per the CFFDRS (Forestry Canada Fire Danger Group) Fire Intensity Classes: <2,000 kW/m (surface fire, Classes I-III combined); 2,000-4,000 kW/m (intermittent crown fire, Class IV); 4,000-10,000 kW/m (continuous crown fire, Class V); >10,000 kW/m (extreme crown fire, Class VI). We mapped fire hazard using a composite of these two variables both split into 4 classes to yield 16 distinct hazard classes of BP and fire intensity.

To identify the spatial source and sink of the most damaging fires relative to the communities within the modeling domains we developed “firesheds”. We intersected the simulated fire polygons created by Burn-P3 with the town site perimeters in each of the modeling domains (BYK: Canmore, Banff, Lake Louise, and Field; Jasper: Jasper; Waterton Lakes: Waterton town site; Riding Mountain: Wasagaming) to identify fires (“problem fires”) that burned into these communities, and then the origin point of each of these fires that burned into the communities was plotted. Fire sinks were calculated by mapping the mean fire size that burned any given pixel (total size of all fires intersecting a given pixel divided by the number of fires that burned that pixel). Fire source dynamics were calculated by using a moving window calculation, whereby the mean fire size generated within an 11 pixel radius of any given pixel was determined (total area burned of all fires originating within an 11 pixel radius of a given pixel, divided by the number of fires originating within that same radius).

4. Domain-Specific Model Inputs

Banff - Yoho – Kootenay National Parks

A general description of data inputs needed for all model domains is provided in Table 6, however more specific information pertaining to Banff-Yoho-Kootenay is provided below in Table 10.

Table 10. Static and stochastic inputs used to model burn probability for Banff, Kootenay and Yoho National Parks.

Model Input	Data Type	Description
Static inputs:		
Fuels	Categorical raster	Canadian Forest Fire Behavior Prediction System fuel type classifications and non-fuel features derived from the Alberta provincial 2017 fuel grid, BC 2004 VRI and PCA Banff NP 2014 VRI. Resolution of 100 m (Figure 7).
Topography	Continuous raster	Canadian Digital Elevation Model data supplied by NRCan at a resolution of 0.75 arc Sec, re-sampled to 100 m resolution (Figure 7).
Seasons	Setting	Start and stop dates for fire weather, grass curing, and deciduous green-up change: - Early Spring = Apr-1 to May-15 (90 % grass curing, leafless broadleaf deciduous) - Late Spring = May-16 to May-31 (80 % grass curing, leafless broadleaf deciduous) - Early Summer = Jun-1 to Jul-31 (05 % grass curing, broadleaf deciduous green-up) - Late Summer = Aug-1 to Aug-31 (65 % grass curing, broadleaf deciduous green-up) - Early Fall = Sep-1 to Sep-15 (80 % grass curing, broadleaf deciduous green-up) - Late Fall = Sep-16 to Sep-30 (100 % grass curing, broadleaf deciduous green-up). (Table 9)
Zones	Categorical raster	No fire zones were created. Weather zones (Figure 7) were included and defined based on Alberta Natural Subregions and BC Biogeographical Ecological classifications (BEC) as well as expert opinion from PCA fire managers. See Figure 2. Zone 1: Upper and Lower Foothills as well as Montane Natural Subregions east of the continental divide shadow. Zone 2: Alpine and Subalpine east of the divide. Zone 3: Montane on the Alberta side and MS and ICH on the BC side Zone 4: Alpine and Subalpine, ESSF and IMA on the BC side Zone 5: Interior Douglas-Fir west of Kootenay National Park

Stochastic inputs:		
Number of fires	Frequency distribution	Number of fires ≥ 3 ha per iteration. Historical records of the number of fires ≥ 3 ha per year were fitted to a negative binomial distribution (Table 9)
Season and cause of fires	Frequency distribution	Based on the historical proportion (%) of fires ≥ 3 ha occurring in each combination of season (early and late, spring, summer, fall) and cause (human, lightning). See Table 9
Spread-event days	Frequency distribution	Derived from historical weather records as the number of consecutive potential fire weather days leading to crown fire, intensity class 4 (RedApp). (Table 8).
Spread hours	Frequency distribution	The number of hours per day a fire is expected to spread was determined as 1/3rd of the daylight hours on the median date of each season. (Table 9)
Ignition locations	Continuous raster	Using a machine-learning model, relative probability surface of human ignition locations was based on the DEM, TPI, solar radiation distance and density to reads and trails. Lightning ignitions were based on DEM, TPI, solar radiation and historical lightning strike data. See Figure 8.
Daily fire weather	Numeric list	Daily weather conditions observed at noon MST and associated Canadian Fire Weather Index (FWI) System codes and indices partitioned by season. We used a FWI threshold of 12 or greater. See Figure 2 for locations of weather stations used.

Fuels

BYK provided Vegetation Resource Inventory (VRI) polygons which use the British Columbia system of describing vegetation. In Yoho and Kootenay National Parks, the VRI is from 2003 aerial photography, and in Banff National Park the VRI is based on 2014 aerial photography. In the 15km buffer around the National Parks, the Alberta Provincial Fuel Grid (from 2020) was used. VRI was converted to FBP using a crosswalk between VRI-and FBP developed by Parks Canada staff, and incorporating some of the methods in Perrakis et al. (2017) in the British Columbia wildfire fuel typing and fuel type layer description.

Where information was lacking in the canopy or understory composition, expert opinion was used to assess the fuel type conversion accuracy. For each of the fuel layers, historical fire perimeters were used to reclassify grass that had burned in the last 15 years to slash (S-2). This method of including burned fires introduces a mosaic forest complex to the fuels layer “aging”

the burned areas to represent a 2018 fuels layer. Previously mentioned spatial layers were merged at 100m resolution encompassing the three National Parks and a 20 km buffer area.

The Burn-P3 model cannot turn fuels “on” or “off” based on snow cover, and thus we modeled Spring and Summer conditions separately for Banff, Kootenay, and Yoho National Park. This was done because the late year snow cover at high elevations prevents fire spread upslope when the valley bottom is snow free and the grass fuels type are cured and available for burning. By summer, high elevation terrain is available for burning but valley bottom grasslands have green standing grasses reducing the availability of fuels for burning. We created a separate “spring” fuel grid by examining snow cover from the 2001-2019 in Banff National Park using the average snowpack annually occurring on May 1. This was done using NDVI remote sensed data and selecting NDVI values <= 1 (which indicate non-vegetated cover, which at this time of year would include rock, snow, ice, and water). We then overrode the fuel calls by assigning these locations as “Non-Fuel”. This “spring” condition represents the average 2001-2019 snowpack in BYK on May 1st, however there is considerable interannual variability in snow cover. Figure 7 (top panels) shows the difference in fuel availability between spring and summer.

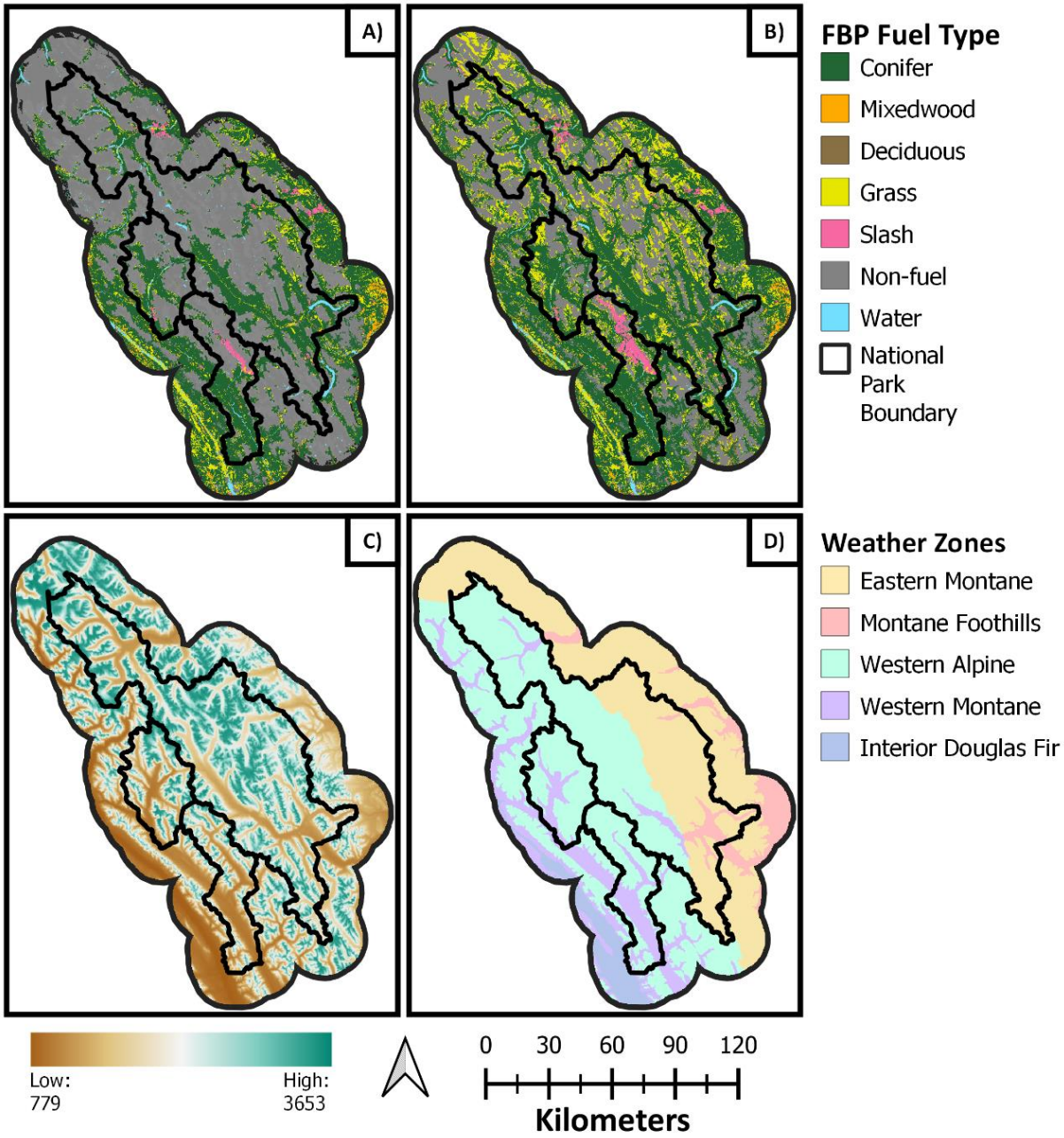

Figure 7. Spatial Inputs for Burn-P3 modelling including A) Spring and B) Summer fuels types based on the FBP (Fire Behaviour Prediction), C) elevation (m) derived from DEM, and D) weather zones based on Alberta Natural Subregions and Biogeographical Ecological Classification (See Figure 2).

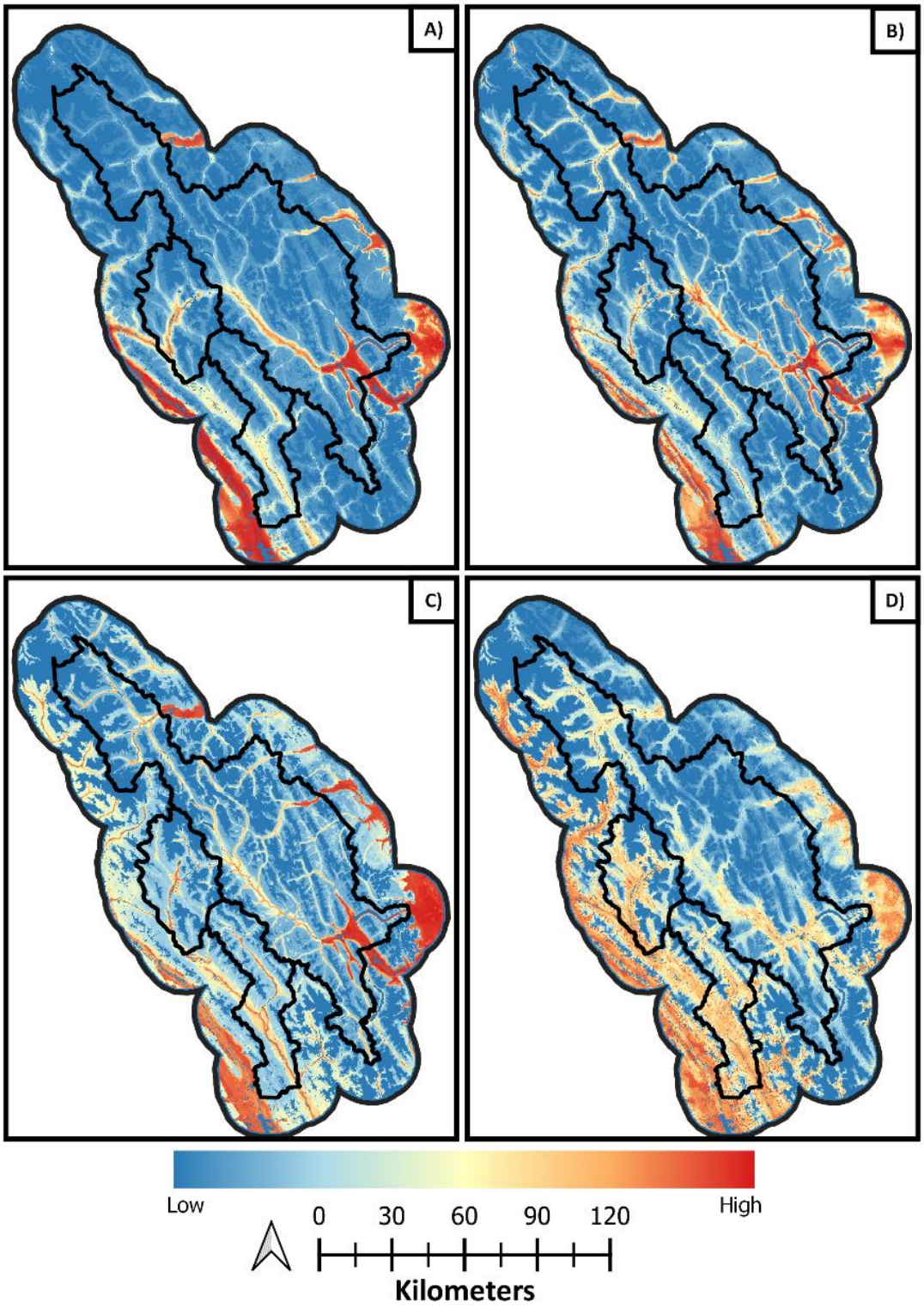

Figure 8. A) Spring, B) Summer, C) Fall Human and D) lightning caused ignition probability (%) grids created using a random forest model based on various spatial data (Distance and density to roads and trails, DEM, TPI, area solar radiation, Historical fire ignition locations and lightning strikes)

No-fuels-Management Fuels

The primary goal of wildfire risk modelling within the Banff national park was to assess the influence of FireSmart, landscape level fuel management, and prescribed fire activities. To perform this analysis a “no-fuels management” fuel grid was necessary. This was developed by intersecting any prescribed fires and fuels management treatments that had spatial information from a 20-year period (2000 – 2019). The fuels intersecting those polygonal or point features were reverted to the Ecological Land Classification that was performed in 1998. The ELC fuels were not modified to simulate growth through time in this study to demonstrate the influence the modification made through prescribed fire and FireSmart treatments would have had. These modifications can be seen in an example area in Figure 9.

To effectively assess the difference between the current era fuels and the pre-treatment fuels this smaller domain was used for a replay of both scenarios. This ensures we are comparing the same potential polygons in both scenarios and the burn probability is not depressed by the broader landscape iteration count. These replays had roughly 85,000 spring and 120,000 summer iterations by comparison to the 500,000 and 750,000 baseline iterations. This smaller number of runs allowed for a more rapid analysis of precisely the same simulated fires.

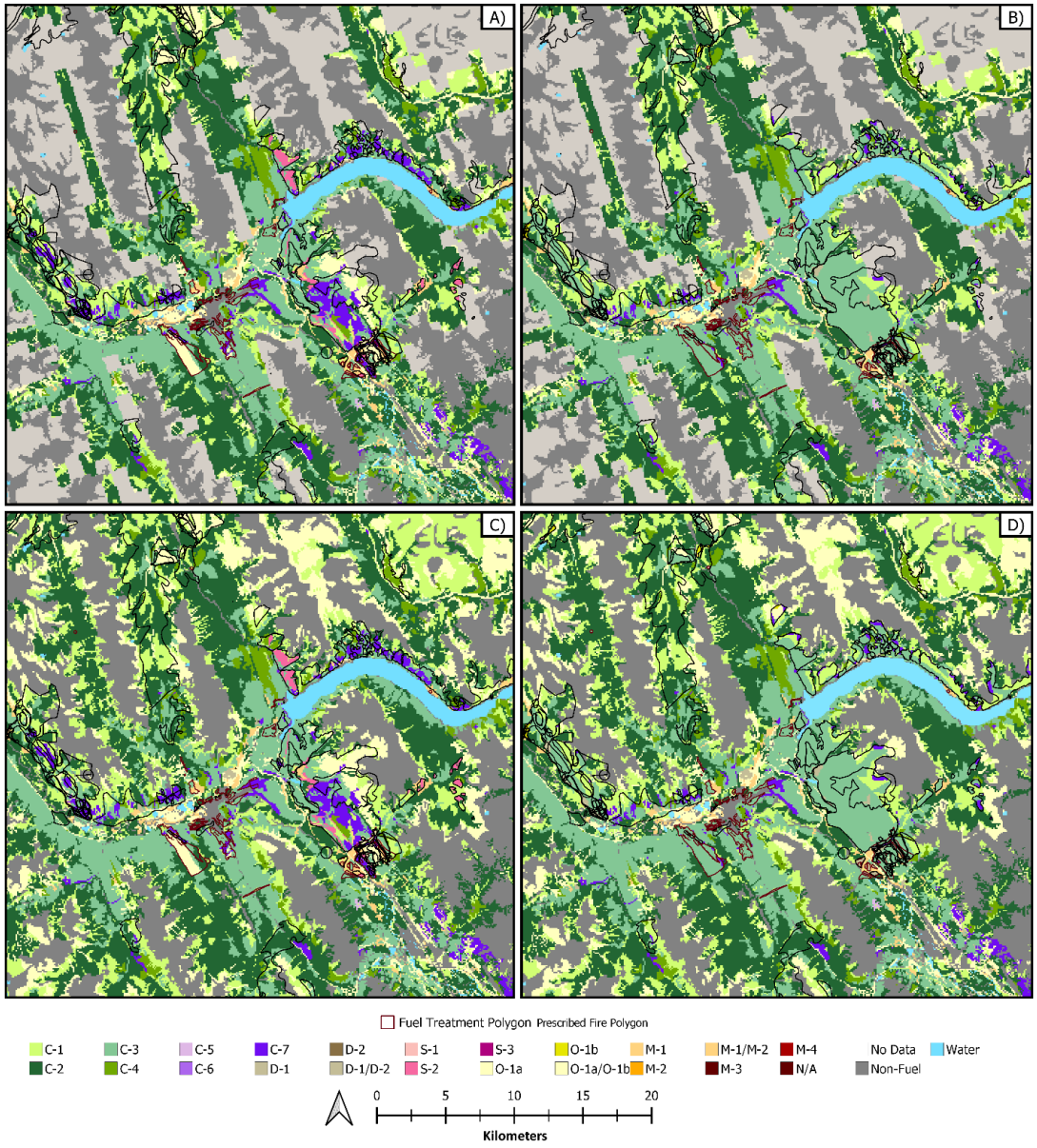

Figure 9. Comparison of A) Current Spring, B) Pre-Treatment Spring, C) Current Summer and D) No-fuels-management Summer Fuels. Black polygons indicate the locations of various fuel treatments applied in the vicinity of Banff town site.

Spread Event Day Distribution

Spread event days (SED) were determined from historical (~100yr) record from the Banff weather station as the number of consecutive fire weather days with potential for crown fire. Normally Burn-P3 model scenarios are constructed using historical fires in the region, and then examining how many days those fires spread for. While we could have done that for BYK, the number of large fires that have occurred on this landscape within the period available to use such an approach (1980 – present day) are highly limited. We also know from historical (and recent) information that large landscape fires are possible within this landscape (see 1910 and 1930-1945 for evidence of massive landscape fires that occurred outside of Banff, as well as 2003 in Southern Alberta, and 2017 both in and out of the Park for examples of major fire runs occurring. Rather than using actual fires to calibrate the SED for BYK, we used the potential for severe fire as determined by FWI indices. As we have data available for more than 100 years due to the early establishment of a weather station in the park, we can examine this period to determine how often weather conditions that are conducive to a major conflagration might occur. We chose weather that resulted in a crown fraction burned of greater than 50% in the C3 fuel type. As such the SED distribution was determined by scanning the historical weather data to determine the historical occurrence of the number of consecutive days with fire weather at this threshold.

Fire History & Seasonality

We examined all fires >3 ha within a buffered distance of 50 kilometers around Banff, Yoho, and Kootenay National Parks to evaluate fire history. Figure 10 shows the total area burned (km^2) and total number of fires for the fire season, seasonal burn patterns, and the differences in human and lightning caused ignitions from 1990 onward. Distinct fire seasons were Spring (Apr-1 to May-31), high human caused fires, low to no lightning caused fires; summer (Jun-1 to Aug-31), high lightning caused fires with few human caused fires; fall (Sept-01 to Sep-30), return to high human caused fires and low lightning caused fires.

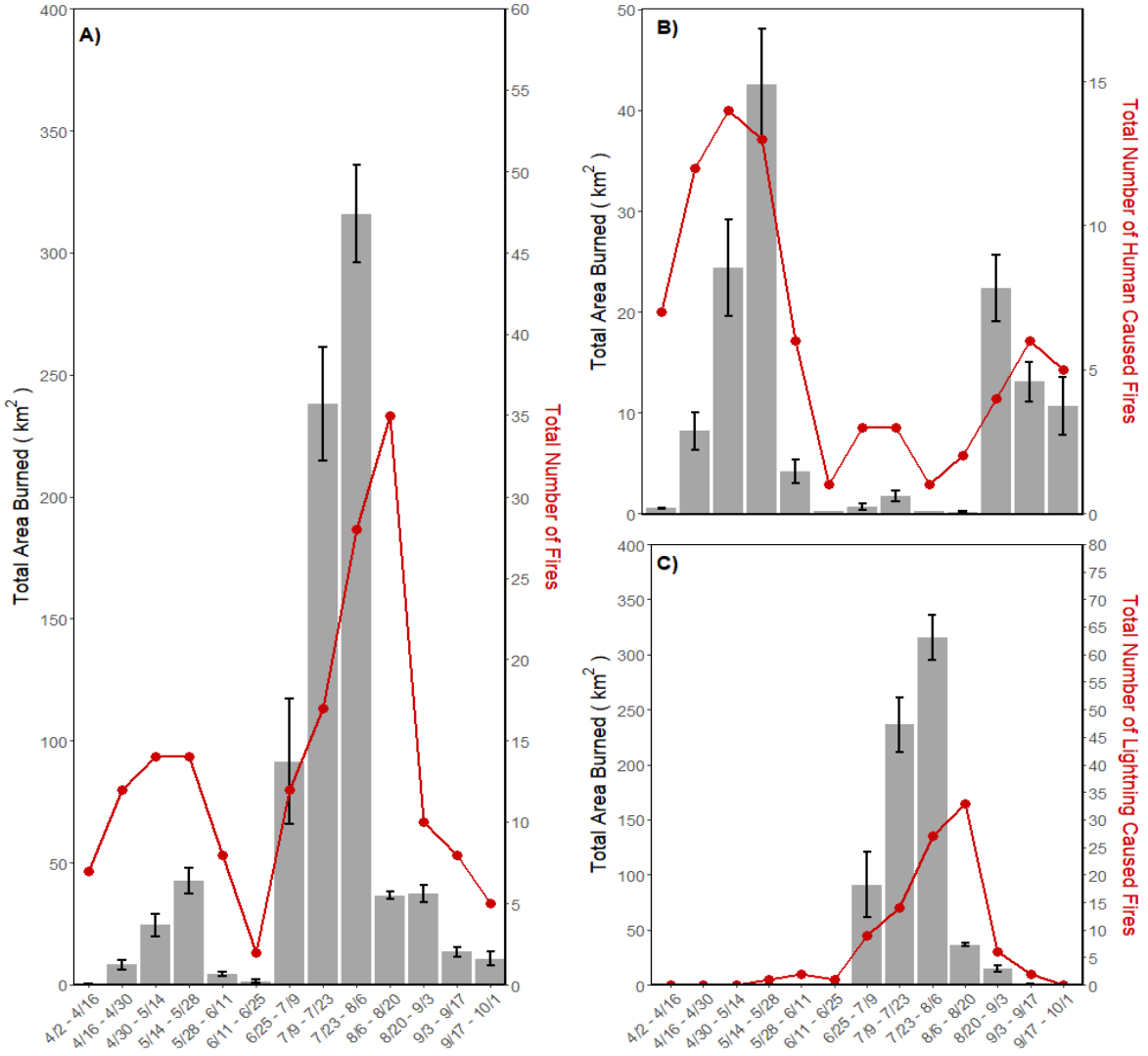

Figure 10. Bi-weekly presentation of burned area (km^2; grey) and the total number of fires (red) greater than 3 ha (A) from the National Fire database buffered to 50km around Banff, Yoho and Kootenay National Parks, as well as the partitioned human (B) and lightning (C) caused fires.

Fire Weather & Weather Zones

Fire weather data was created from the Alberta (ACIS, 1973-2017) stations and Environment and Climate Change Canada, Meteorological Survey of Canada (MSC, 1988-2017) weather stations. In total 90 weather stations were included within the model domain (National Parks and buffer area). Fire weather indices (FWI) were calculated from the temperature,

precipitation, relative humidity, wind speed and direction. Station data was filtered to only include weather from March 01 to October 31, with a crown fraction burned in C-3 of 50% or greater. Those remaining fire weather days were assigned a season. A general description of inputs required for the Burn-P3 model was provided in Table 6, however more specific information pertaining to Banff-Yoho-Kootenay is provided in Table 10. Weather zones (Figure 7) were included and defined based on Alberta Natural Subregions (NSRs) and British Columbia Biogeographical Ecological classifications (BEC zones) (Figure 2). Zones were classified as follows:

- Zone 1 (Montane Foothills), includes Upper and Lower Foothills NSRs of as well as the Montane NSR east of the continental divide shadow (18 weather stations)
- Zone 2 (Eastern Alpine), includes the Alpine and Subalpine NSRs east of the divide (24 weather stations)
- Zone 3 (Western Montane), includes the Montane NSR west of the divide and the Montane Spruce (MS) and Interior Cedar-Hemlock (ICH) BEC zones (6 weather stations)
- Zone 4 (Western Alpine), include Alpine and Subalpine NSRs west of the continental divide shadow, and Engelmann Spruce-Subalpine Fir (ESSF) and Interior Mountain-heather/alpine (IMA) BEC zones (38 weather stations)
- Zone 5 (Interior Douglas-Fir), due to the wet low elevation classified as Interior Douglas-Fir west of Kootenay National Park within the buffer of the modelling domain, this zone was kept separate from zone 3 (4 weather stations)
- Zones 1, 3, and 5 are low elevation, east, central, and west, respectively. While zones 2 and 4 are higher elevation alpine and subalpine to the east and central, respectively.

Jasper National Park

A general description of inputs required for the Burn-P3 model was provided in Table 6, however more specific information pertaining to Jasper is provided below in Table 11.

Table 11. Static and stochastic inputs used to model burn probability of Jasper National Park.

Model Input	Data Type	Description
Static inputs:		
Fuels	Categorical raster	Canadian Forest Fire Behavior Prediction System fuel type classifications and non-fuel features derived from spatial vegetation provided by the National Park, area within buffer is the Alberta provincial 2017 fuel grid. Resolution of 100 m (Figure 11**Error! Reference source not found.**).
Topography	Continuous raster	Canadian Digital Elevation Model data supplied by NRCan at a resolution of 0.75 arc Sec, re-sampled to 100 m resolution (Figure 11).
Seasons	Setting	Start and stop dates for fire weather, grass curing, and deciduous green-up change: - Spring = Apr-1 to May-30 (75 % grass curing, leafless broadleaf deciduous) - Summer = Jun-1 to Aug-15 (25 % grass curing, broadleaf deciduous green-up) - Fall = Aug-16 to Sep-30 (90 % grass curing, broadleaf deciduous green-up). (Table 9)
Zones	Categorical raster	No zones included
Stochastic inputs:		
Number of fires	Frequency distribution	Number of fires ≥ 3 ha per iteration. Historical records of the number of fires ≥ 3 ha per year were fitted to a negative binomial distribution. (Table 9)
Season and cause of fires	Frequency distribution	Based on the historical NFDB proportion (%) of fires ≥ 3 ha occurring in each combination of season (spring, summer, and fall) and cause (human, and lightning). See Table 9
Spread-event days	Frequency distribution	Derived from historical weather records as the number of consecutive potential fire weather days leading to crown fire, intensity class 4 (RedApp). See Table 8
Spread hours	Frequency distribution	The number of hours per day a fire is expected to spread was determined as 1/3 of the daylight hours on the median date of each season. (Table 9)
Ignition locations	Continuous raster	Using a Random Forest Model, relative probability surface of human ignition locations was based on the DEM, TPI, solar radiation distance and density to reads and trails. Lightning ignitions were based on DEM, TPI, solar radiation and historical lightning strike data. (Figure 12)
Daily fire weather	Numeric list	Daily weather conditions observed at noon MST and associated Canadian Fire Weather Index (FWI) System codes and indices partitioned by season. We used a FWI threshold of 12 or greater. See Figure 3 for locations of weather stations used.

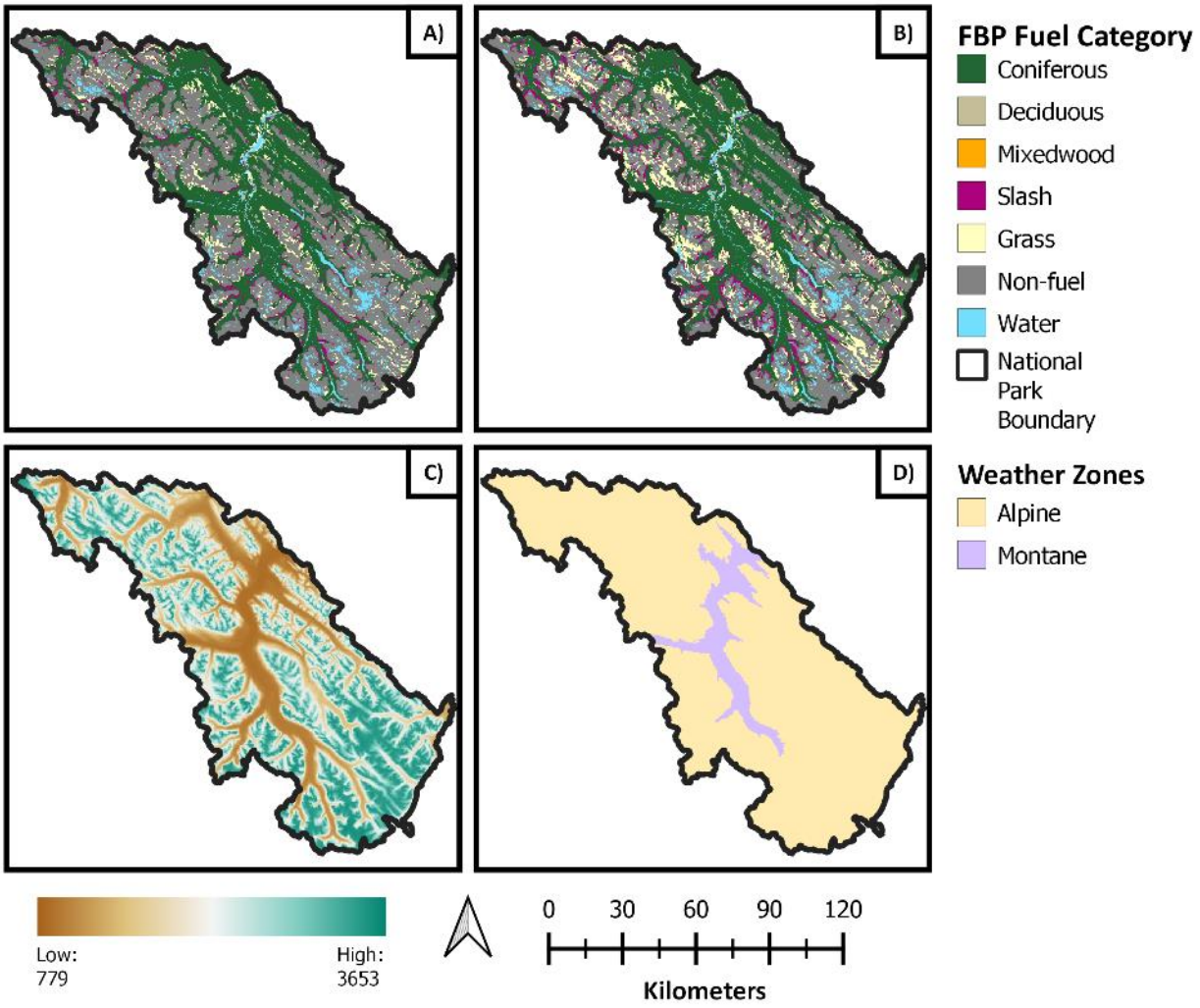

Figure 11. Spatial Inputs for Burn-P3 modelling including fuels types based on the A) Spring and B) Summer FBP (Fire Behaviour Prediction) fuels, C) elevation (m) derived from DEM, and D) weather zones.

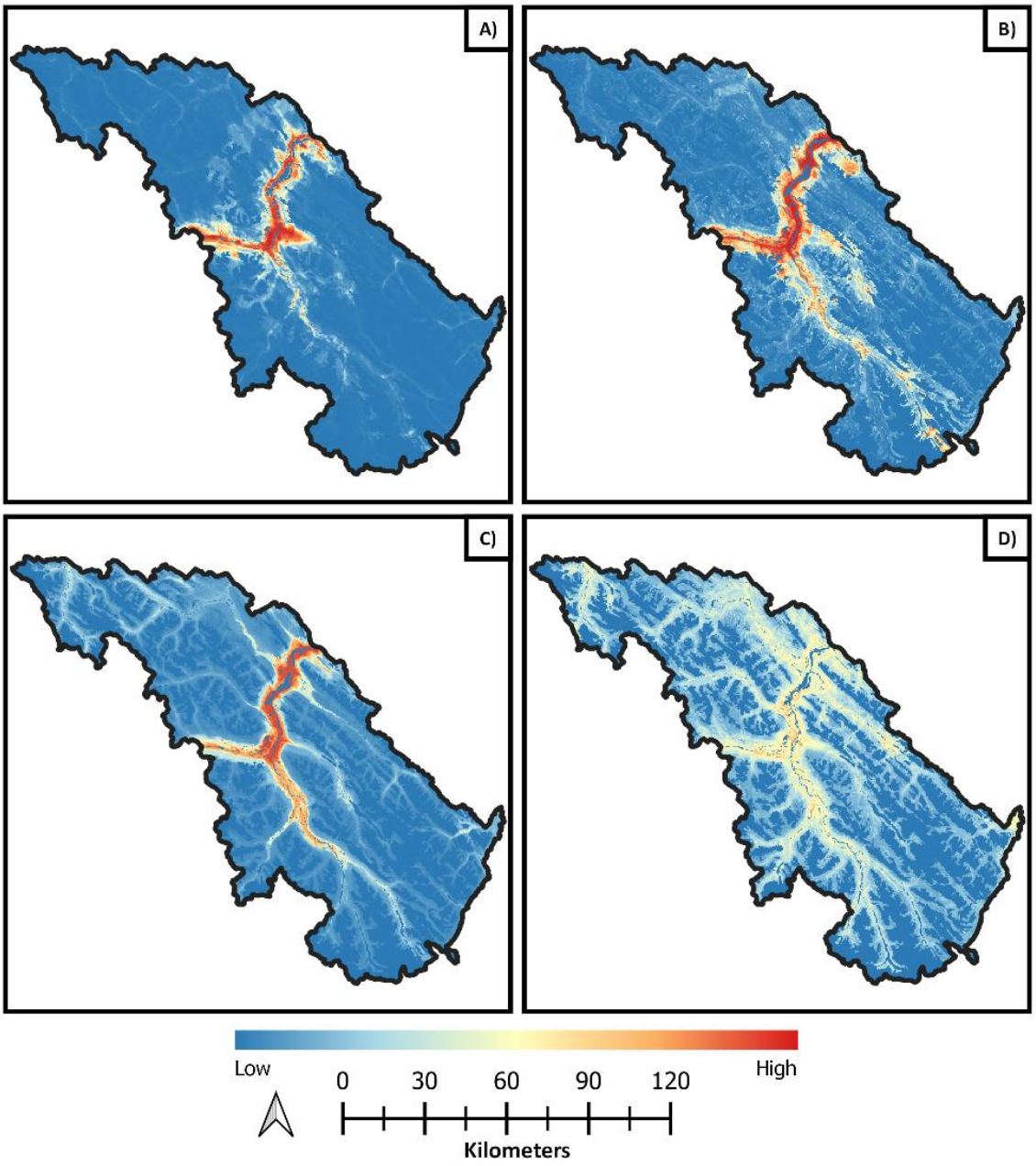

Figure 12. A) Human-caused spring, B) Human-caused summer C) Human-caused fall and D) Lightning-caused ignition probability grids for Jasper National Park.

Fuels

The Ecological Land Classification (imagery from 1971) is the most current full-landscape vegetation spatial coverage for Jasper National Park. Polygons from this coverage were converted to 100m raster cells and reclassified to FBP fuel types based on expert opinions and previous research (Perrakis et al. 2017). The ELC data only covered the landscape of the National Park itself, and the buffer area surrounding the Park had to be filled in using the Alberta Fuel Grid (2020) to the east and the British Columbia Fuel Grid (2020) to the west (see Banff/Fuels for further description of these layers). For each of the fuel layers, areas within historical fires occurring since the date of the respective inventory were reclassified according to Table 7.

In recent years, Mountain Pine Beetle (MPB) has had a large influence on forest structure, and therefore fuel type. To address the impact of MPB on fire behaviour we examined the year and severity of MPB attack throughout the landscape. Areas attacked prior to 2014 were considered to have dropped all needles ("grey stage"), while those from 2014-2018 were considered to still have dead needles ("red stage"). However, the 2018 MPB attack was so widespread that there was no spatially explicit older attack, and therefore it was all classified as "red-stage", and assigned to fuel type "mixedwood 65 percent dead fir (M-3 65 PDF), as per Perrakis et al. (2017). There is considerable ongoing research on MPB effects on fire behaviour, and which FBP fuel type is best used to represent these changes, and at the present time, M-3 65 represents the best consensus reached among fire behavior experts. A comparison of the fuels as they appear in the fuel grid currently and the Mountain Pine Beetle substitution can be seen in Figure 13.

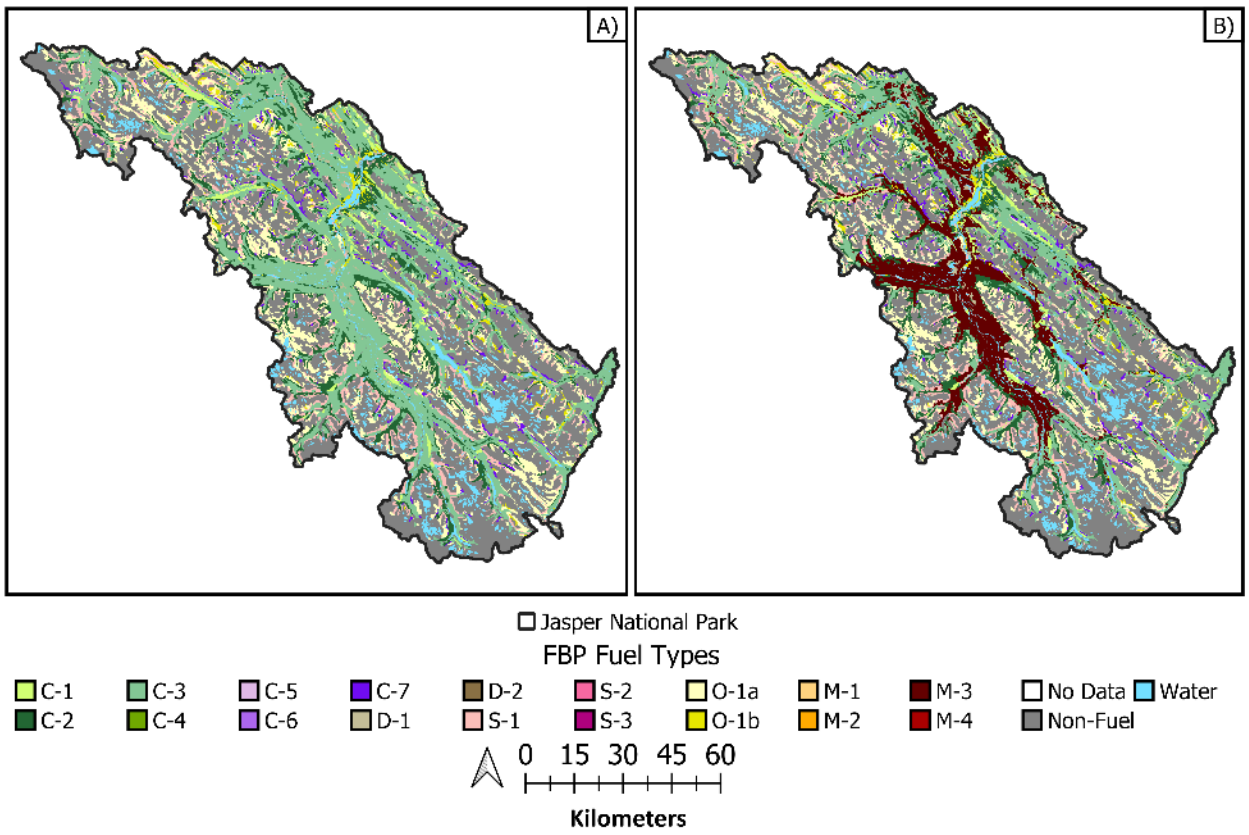

Figure 13. Comparison of fuels A) before and B) after C-3 Lodgepole Pine was reclassified into M-3 65 Percent Dead Fir

Fire History & Seasonality

We examined all fires >3 ha within a buffered distance of 50 kilometer around Jasper National Park to evaluate fire history. Figure 14 shows the total area burned (km^2) and total number of fires for the fire season, seasonal burn patterns and the differences in human and lightning caused ignitions from 1990 onward. Distinct fire seasons were Spring (Apr-1 to May-31), Summer (Jun-1 to Aug-15), and Fall (Aug-16 to Sep-30).

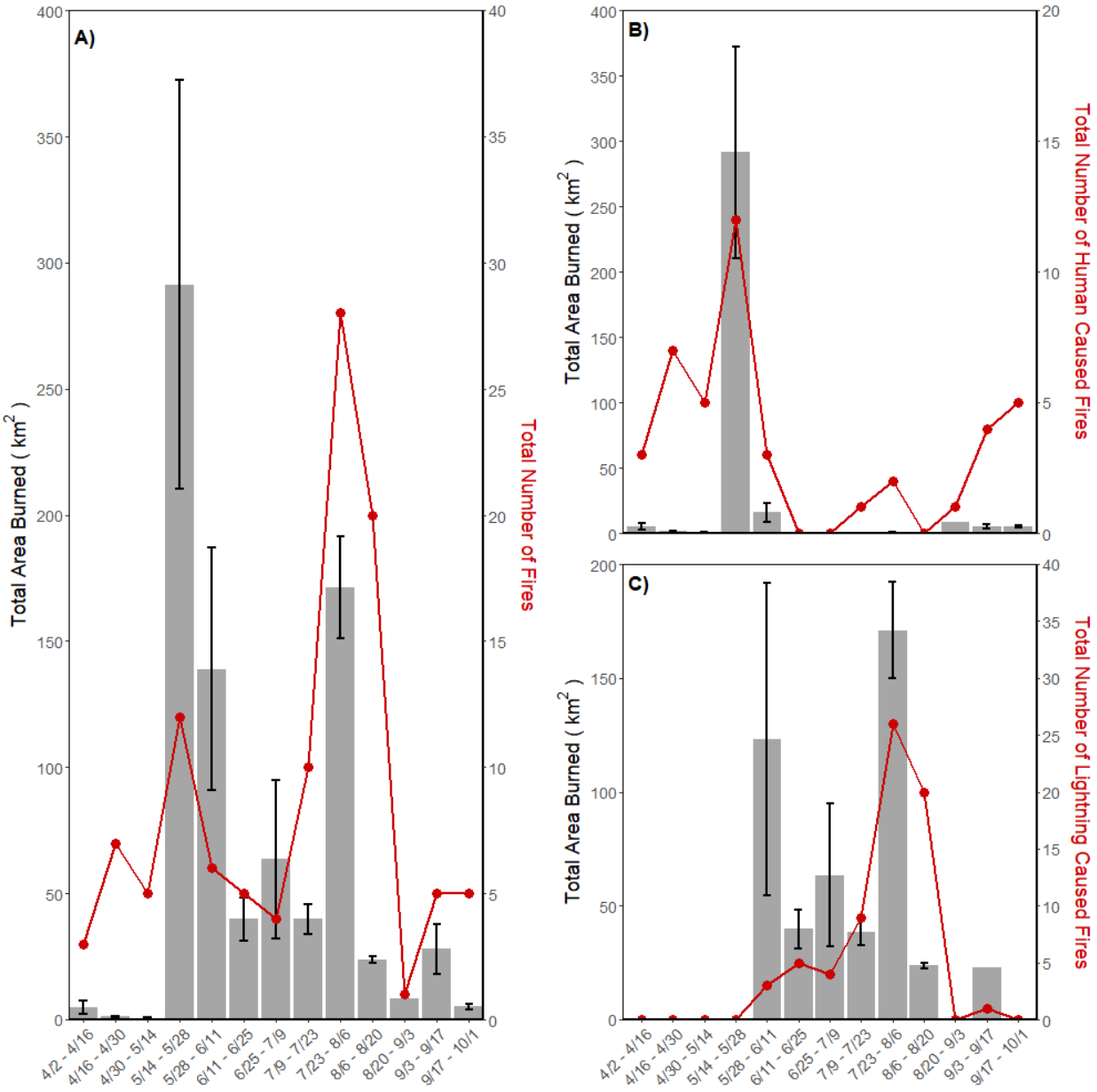

Figure 14. Bi-weekly presentation of burned area (km^2; grey) and the total number of fires (red) greater than 3 ha (A) from the National Fire database buffered to 50km around Jasper National Park, as well as the partitioned human (B) and lightning (C) caused fires.

Fire Weather & Weather Zones

Fire weather data was acquired from the Alberta (ACIS, 1973-2017) stations and the Environment and Climate Change Canada, Meteorological Survey of Canada (MSC, 1988-2017) weather stations. In total 50 weather stations were included within the model spatial domain (National Park and 15km buffer area). Fire weather indices (FWI) were calculated from the temperature, precipitation, relative humidity, wind speed and direction. Station data was filtered to only include weather between April 01 and October 31, inclusively, when the crown fraction burned in M-3 (65% dead fir) is greater than 50%. Those remaining fire weather days were assigned a season (Table 11.

Table 11). Two weather zones were included for Jasper National Park, Montane and Alpine (Figure 11).

Waterton Lakes National Park

A general description of inputs required for the Burn-P3 model was provided in Table 6, however more specific information pertaining to Waterton is provided below in Table 12.

Table 12. Static and stochastic inputs used to model burn probability for Waterton Lakes National Park.

Model Input	Data Type	Description
Static inputs:		
Fuels	Categorical raster	Canadian Forest Fire Behavior Prediction System fuel type classifications and non-fuel features derived from spatial vegetation provided by the National Park which originates from vegetation data produced by Glacier NP, USA. Area within the buffer is the Alberta provincial 2017 fuel grid and the BC 2014 fuels layer. Resolution of 100 m (Figure 15).
Topography	Continuous raster	Canadian Digital Elevation Model data supplied by NRCan at a resolution of 0.75 arc Sec, re-sampled to 100 m resolution. See Figure 15.
Seasons	Setting	Start and stop dates for fire weather, grass curing, and deciduous green-up change: - Spring = Apr-1 to May-15 (90 % grass curing, leafless broadleaf deciduous) - Early Summer = May-16 to Jul-15 (10 % grass curing, broadleaf deciduous green-up) - Late Summer = Jul-16 to Aug-30 (50 % grass curing, broadleaf deciduous green-up) - Fall = Sep-01 to Sep-30 (100 % grass curing, broadleaf deciduous green-up). (Table 9)

Stochastic inputs:		
Number of fires	Frequency distribution	Number of fires ≥ 3 ha per iteration. Historical records of the number of fires ≥ 3 ha per year were fitted to a negative binomial distribution. (Table 9)
Season and cause of fires	Frequency distribution	Based on the historical NFDB proportion (%) of fires ≥ 3 ha occurring in each combination of season (spring, summer, fall) and cause (human, lightning). See Table 9
Spread-event days	Frequency distribution	Derived from historical weather records as the number of consecutive potential fire weather days leading to crown fire, intensity class 4 (RedApp). See Table 8
Spread hours	Frequency distribution	The number of hours per day a fire is expected to spread was determined as 1/3 of the daylight hours on the median date of each season. (Table 9)
Ignition locations	Continuous raster	Using a RandomForestModel, relative probability surface of human ignition locations was based on the DEM, TPI, solar radiation distance and density to reads and trails. Lightning ignitions were based on DEM, TPI, and solar radiation. See Figure 15.
Daily fire weather	Numeric list	Daily weather conditions observed at noon MST and associated Canadian Fire Weather Index (FWI) System codes and indices partitioned by season. We used a FWI threshold of 12 or greater. See Figure 4 for locations of weather stations used.

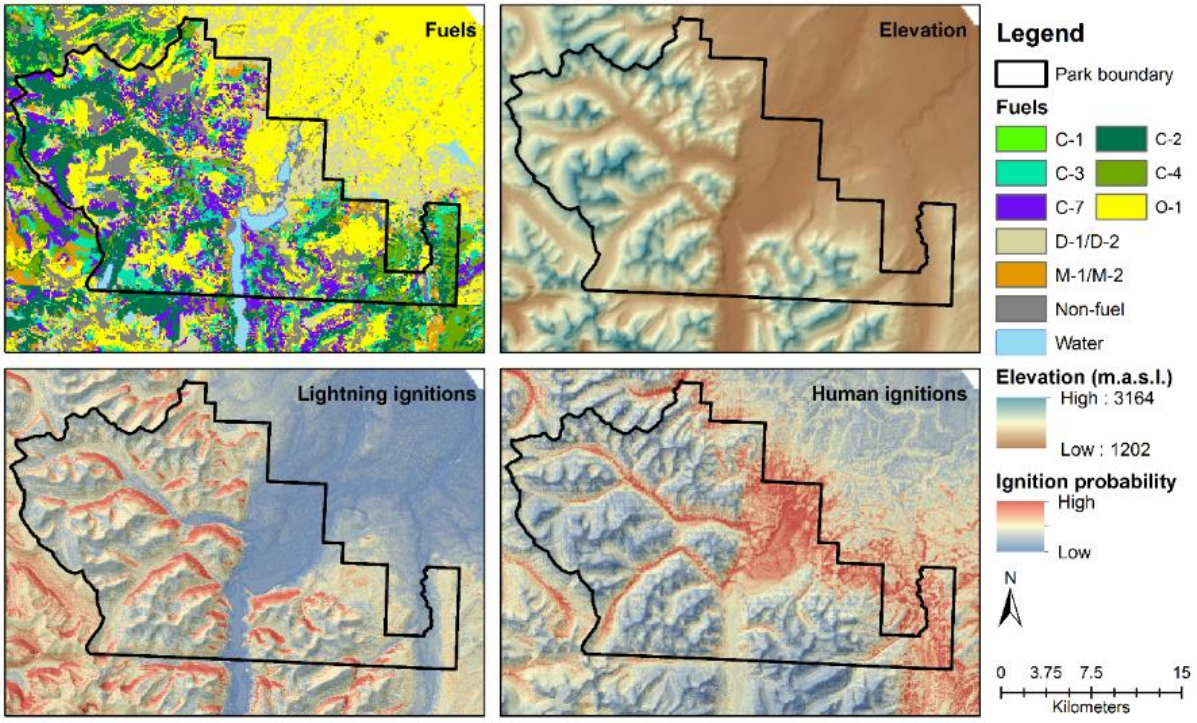

Figure 15. Spatial Inputs for Burn-P3 modelling including fuels types based on the FBP (Fire Behaviour Prediction), elevation (m) derived from DEM, and Human and Lightning caused probability (%) ignition grids created using a random forest model based on various spatial data (Distance and density to roads and trails, DEM, TPI, area solar radiation, Historical fire ignition locations and lightning strikes) for Waterton Lakes National Park, AB, Canada.

Fuels

Waterton Lakes National Park, AB, Canada, is located on multiples borders, those of the Canadian provinces of Alberta and British Columbia, as well as on the border of Canada and the United States. Due to the location of Waterton Lakes National Park multiple sources of vegetation data was used. Waterton Lakes National Park field unit provided a vegetation mapping inventory (VMI) vector shapefile. The VMI in Waterton Lakes was flown as an extension of the VMI for Glacier National Park, Montana, USA. In the buffer area around the National Park, 3 other datasets are used, the VMI for Glacier National Park to the South, the Alberta fuels layer (2015) to the east and the British Columbia fuels layer (2013) west of Waterton Lakes National Park. British Columbia and Alberta fuels grid were already classified using the FBP system compatible with Burn-P3 modelling domain.

VMI for Waterton Lakes and Glacier National Parks had to be converted to FBP fuel types based principally on the MAP_CLASS variables, certain types also included CANOPY and HEIGHT. Canopy was classed into three categories, sparse 0-25% vegetation cover, open 25-60% and closed, > 60% vegetation overstory. Height of trees was also categorized into four groups, greater than 30m, 15-30m, 5-15m, and 0.5-5m. See Table 13 classification of each vegetation class into fuel type.

The VMI, Alberta and British Columbia fuels layers were resampled to 100m resolution and merged giving importance to the VMI, followed by the Alberta fuels layer and finally the British Columbia fuels grid. Wildfires not included on the fuels landscape and those which have burnt post creation of the fuel grids were added to the grids following a state in transition rules previously stated (Table 7).

Waterton Lakes National Park was modelled twice: once with 2017 fuels, which comprises the merged three fuels layers and including the fires up to the summer of 2017; the second model run for Waterton Lakes National Park landscape included the Kenow wildfire (September 2017). As such we modelled the pre-Kenow fire landscape and post-Kenow (aka the current landscape) in 2018.

Table 13. Classification of the vegetation mapping inventory (VMI) project as per the FBP fuel classification for Waterton Lakes National Park, Alberta, CA and Glacier National Park, Montana, USA. Classification into fuel types are based on the vegetation class as well as the canopy closure and dominant vegetation height. Canopy closure is classified into three categories as follows: Sparse (0-25%), Open (25-60%), and Closed (>60%).

Fuel types	Vegetation class
O-1	Dwarf-shrub/herbaceous complex: mesic – wet & dry - mesic, White dryad dwarf-shrubland, Krummholz shrubland, Deciduous shrubland, Grassland herbaceous, Mixed regenerated shrubland, Sparse (0.5-5m) lodgepole pine forest, Sparse (0.5-5m) Douglas-fir woodland.
C-2	Sparse subalpine fir – Engelmann spruce forest, Sparse Engelmann spruce woodland, Sparse Engelmann spruce – wet shrub forest, Subalpine fir- Engelmann spruce forest.
C-3	Sparse whitebark pine woodland, Open Engelmann spruce forest, Open Engelmann spruce – wet shrub forest, Open lodgepole pine woodland, Open (5-15m) lodgepole pine forest, Closed (5-15m) Douglas-fir forest, Open subalpine fir – Engelmann spruce woodland, Open subalpine fir – Engelmann spruce forest.
C-4	Sparse (5-15m) lodgepole pine forest.
C-7	Limber pine woodland, Open whitebark pine, Closed lodgepole pine woodland, Open (15-30m) Douglas-fir forest, Closed subalpine fir – Engelmann spruce woodland.
D-1/D-2	Black cottonwood forest, Poplar – birch forest, Deciduous shrubland, Subalpine larch woodland.
M-1/M-2	Mixed conifer – deciduous forest, Mixed conifer – deciduous wet forest, Mixed conifer – deciduous shrubland.
NON-FUEL	Residential/commercial areas and rail roads, glacier/snowfield
WATER	Streams, rivers, natural/artificial pond/lakes

Fire History & Seasonality

We examined all fires >3 ha within a buffered distance of 50 kilometer around Waterton Lakes National Park to evaluate fire history. Historical fire points were from the Canadian National Fire database (NFDB) as well as added historical fire points from Glacier National Park, USA. Figure 16 shows total area burned (km^2) and total number of fires for the fire season, seasonal burn patterns, as well and the differences between human and lightning caused

ignitions since 1990. Distinct fire seasons were Spring (Apr-1 to May-15), few human-caused fires only; summer (May-16 to Aug-31), lightning caused fire activity with little human activity; fall (Sept-01 to Sep-30), no lightning caused fires and high human caused fires. Due to the low number of historical fires despite our efforts to include the Canadian and American databases, seasonality was determined using expert opinions from the parks fire manager based on aspen leaf-out and grass curing.

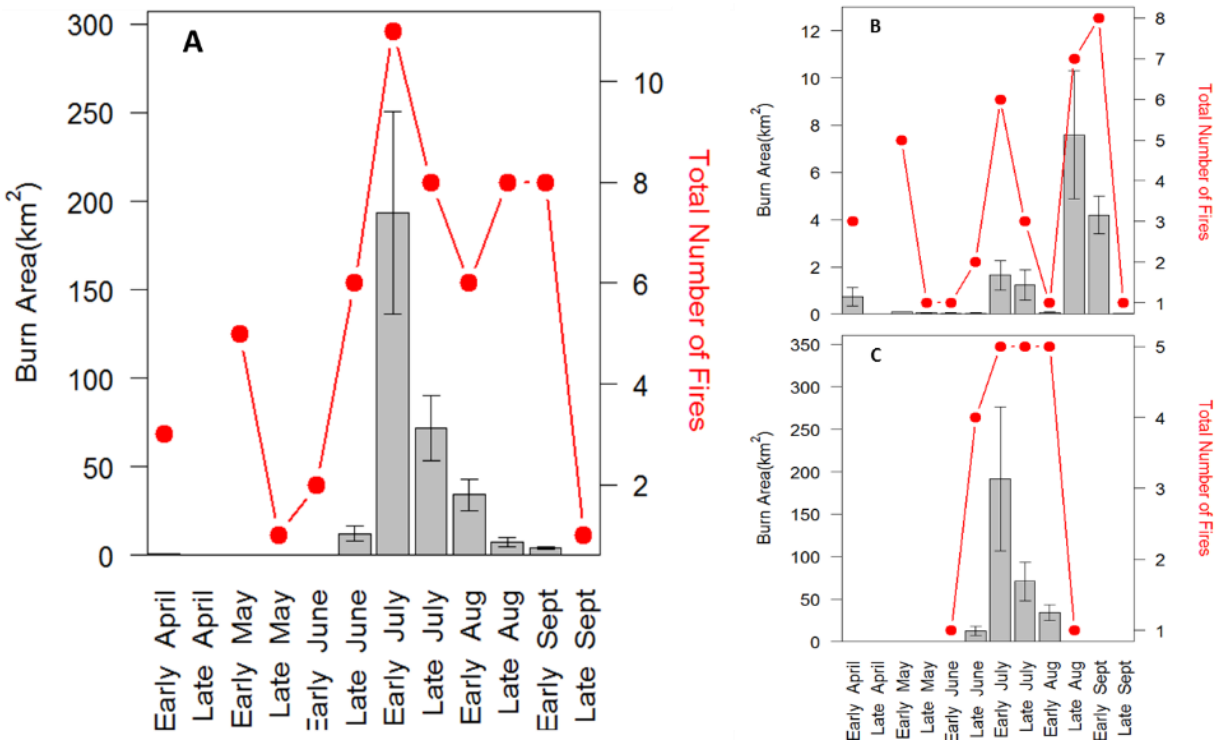

Figure 16. Bi-weekly burned area (km^2; grey) and the total number of fires (red) greater than 3ha (A) from the National Fire database buffered to 50km around Waterton Lakes National Park, as well as the partitioned human (B) and lightning (C) caused fires.

Fire Weather & Weather Zones

Fire weather data was gathered from multiple sources due to the lack of meteorological stations having all necessary measurements for fire weather indices (FWI) calculation. Data was gathered from the Alberta (ACIS, 1974-2017) stations, Environment and Climate Change Canada (MSC, 1988-2017) weather stations, British Columbia wildfire weather stations (FLNRO-WMB, 1979-2018), Waterton Park Warden Office (PCA, 1943-2017), and Goat Haunt station (NPS, 2005-2017). In total only 18 weather stations were included within the model domain (National

Park and 15km buffer area). Fire weather indices (FWI) were calculated from the temperature, precipitation, relative humidity, wind speed and direction. Station data was filtered to only include weather between April 01 and September 30, inclusively, with an FWI greater or equal to 12, and were assigned a season (Table 12). Zones were not included for Waterton Lakes National Park as there were very few weather stations from which to extract data to spatially differentiate weather zones within the park.

Riding Mountain National Park

A general description of inputs required for the Burn-P3 model was provided in Table 6, however more specific information pertaining to Riding Mountain is provided below in Table 14.

Table 14. Static and stochastic inputs used to model burn probability for Riding Mountain National Park, MN, Canada.

Static inputs:		
Fuels	Categorical raster	Canadian Forest Fire Behavior Prediction System fuel type classifications and non-fuel features derived from spatial vegetation provided by the National Park which encompasses the buffer area. Resolution of 100 m (Figure 17).
Topography	Continuous raster	Canadian Digital Elevation Model data supplied by NRCan at a resolution of 0.75 arc Sec, re-sampled to 100 m resolution (Figure 17).
Seasons	Setting	Start and stop dates for fire weather, grass curing, and deciduous green-up change: - Spring = Apr-1 to May-15 (90 % grass curing, leafless broadleaf deciduous) - Summer = May-16 to Aug-15 (10 % grass curing, broadleaf deciduous green-up) - Fall = Aug-16 to Sep-30 (100 % grass curing, broadleaf deciduous green-up). (Table 9)
Stochastic inputs:		
Number of fires	Frequency distribution	Number of fires ≥ 3 ha per iteration. Historical records of the number of fires ≥ 3 ha per year were fitted to a negative binomial distribution. (Table 9)
Season and cause of fires	Frequency distribution	Based on the historical NFDB proportion (%) of fires ≥ 3 ha occurring in each combination of season (spring, summer, fall) and cause (human, lightning). See Table 9
Spread-event days	Frequency distribution	Derived from historical weather records as the number of consecutive potential fire weather days leading to crown fire, intensity class 4 (RedApp). See Table 8.
Spread hours	Frequency distribution	The number of hours per day a fire is expected to spread was determined as 1/3 of the daylight hours on the median date of each season (Table 9).
Ignition locations	Continuous raster	Using a Random Forest Model, relative probability surface of human ignition locations was based on the DEM, TPI, solar radiation distance and density to reads and trails. Lightning ignitions were based on DEM, TPI, and solar radiation (Figure 17).
Daily fire weather	Numeric list	Daily weather conditions observed at noon MST and associated Canadian Fire Weather Index (FWI) System codes and indices partitioned by season. We used a FWI threshold of 12 or greater.

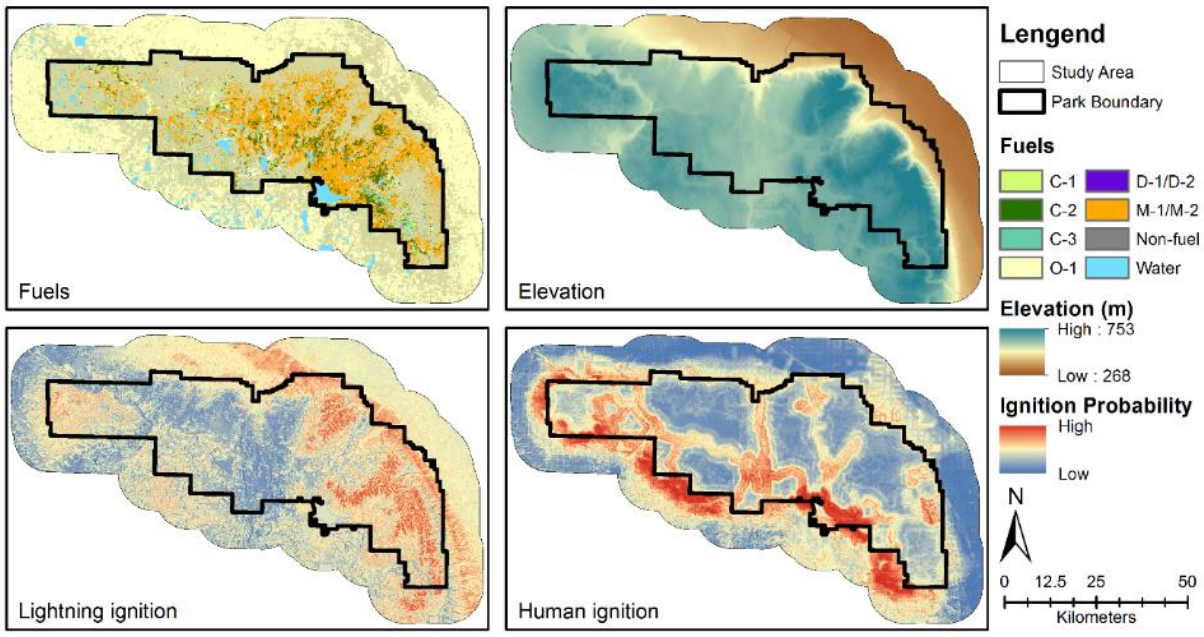

Figure 17. Spatial Inputs for Burn-P3 modelling including fuels types based on the FBP (Fire Behaviour Prediction), elevation (m) derived from DEM, and Human and Lightning caused probability (%) ignition grids created using a random forest model based on various spatial data (Distance and density to roads and trails, DEM, TPI, area solar radiation, Historical fire ignition locations and lightning strikes) for the park and a 10km buffer around Riding Mountain National Park, MN, Canada.

Fuels

FBP fuel types were converted from vegetation maps based on expert opinions and previous research (Perrakis et al. 2017). Spatial vegetation data (1997) was provided by the Riding Mountain field unit based on the 1993 LANDSAT imagery with grid resolution of 30m. This vegetation layer covered the extent of the 10km buffer around the park. Conversion from vegetation classes to FBP fuel type were completed using expert opinion of the vegetation map legend descriptions (Table 15). Given the large amount and variability of wetlands within the park, if the vegetation classification of wetlands overlapped with the vector file of waterbodies the corresponding fuel type is non-fuel (NF), otherwise wetlands were classified as grasslands (O-1). Originally the model was run with agricultural lands as non-fuel, however due to the parks concern regarding the potential for escaped agricultural burns entering the park, agricultural lands were converted to grasslands with a low fuel load to allow these fires to occur in the model.

Table 15. Classification into FBP fuel types are based on the vegetation types classed from the 1993 LANDSAT imagery for Riding Mountain National Park, Manitoba, CA.

Fuel type	Vegetation class
O-1	Grasslands, Agriculture, Low shrub land, and wetlands
C-1	Open canopy deciduous forest
C-2	Closed canopy coniferous forest
C-3	Regenerating coniferous forest
D-1/D-2	Shrubland, Aspen parkland, and Eastern deciduous forest
M-1/M-2 20PC	Bur oak forest
M-1/M-2 25PC	Deciduous canopy – coniferous subcanopy forest
M-1/M-2 50PC	Mixed canopy (deciduous-coniferous) forest
NF/WATER	Open waterbodies and permanent wetlands

Fire History & Seasonality

We examined all fires >3 ha within the Boreal Plains ecoregion to incorporate a larger area due to the small sample size of historical fires given fire suppression practices and the vast expanse of agricultural lands surrounding the park. Historical fire points used were from the Canadian National Fire database (NFDB). Total area burned (km^2) and total number of fires are depicted in Figure 18 bi-weekly for the fire season, April to September inclusively, as well as the human and lightning caused ignition partitions. The total number of fires bi-weekly shows the seasonality in fire patterns for Riding Mountain National Park and the Boreal Plains ecoregion. Season were selected as follows: Spring (Apr-1 to May-15), few human caused fires and no lightning caused fires; summer (May-16 to Aug-15), high lightning and human caused fire activity; fall (Aug-16 to Sep-30), little to no human and lightning caused fires.

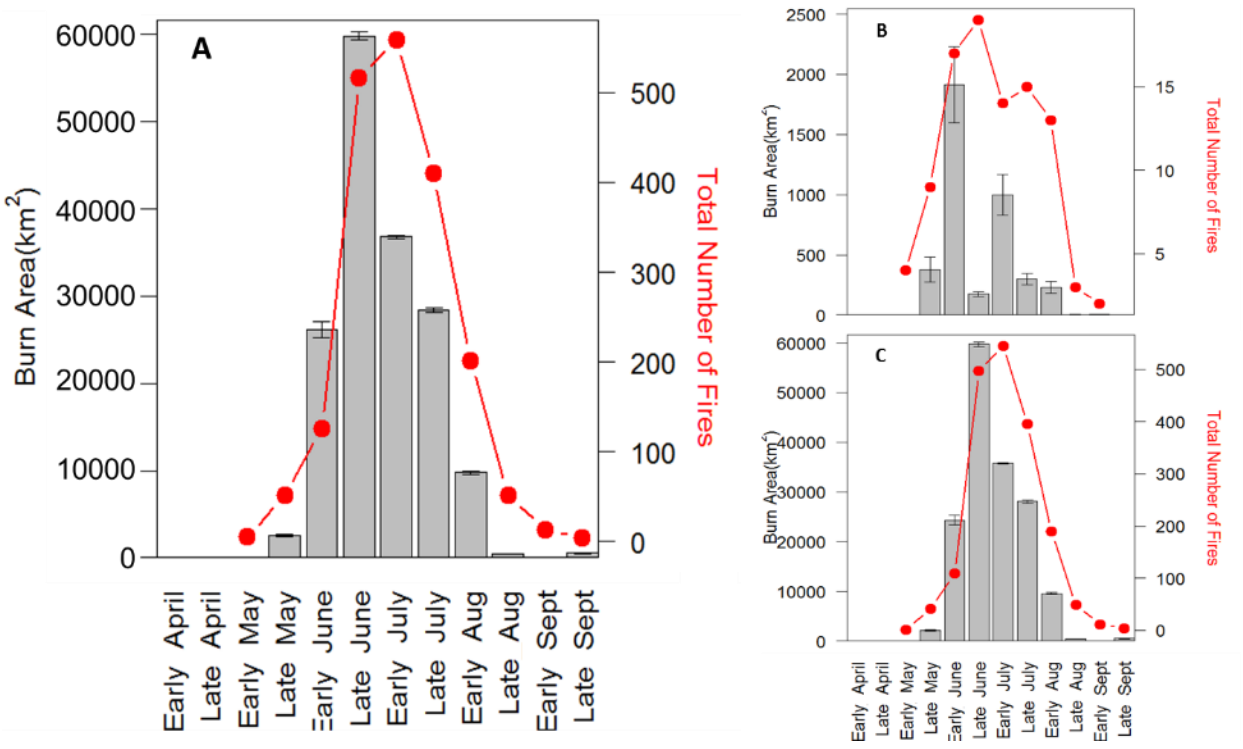

Figure 18. Bi-weekly burned area (km^2; grey) and the total number of fires (red) greater than 3ha (A) from the National Fire database for the ecoregion of the Boreal Plains which includes Riding Mountain National Park, as well as the partitioned human (B) and lightning (C) caused fires.

Fire Weather & Weather Zones

Fire weather data was gathered from Environment and Climate Change Canada, Meteorological Survey Canada (MSC, 1988-2017) weather stations. In total only 6 weather stations were included within the model domain (National Park and 15km buffer area). Fire weather indices (FWI) were calculated from the temperature, precipitation, relative humidity, wind speed and direction. Station data was filtered to only include weather between April 01 and September 30, inclusively, with an FWI greater or equal to 12. Those remaining fire weather days were assigned a season

Zones were not included for Riding Mountain National Park as there was no significant variation in mean annual temperature and mean annual precipitation across the modelling domain.

5. Results

These burn probability values do not represent annual expectations of fire occurrence in the typical usage of the Burn-P3 model (Parisien et al. 2005), as we only modeled a single fire in every iteration (as opposed to a range in the numbers of fires based on historical conditions). Instead, these BP values represent the likelihood of a particular location burning given the conditions of a) a single fire occurring; b) that fire occurring above the threshold of Initial Spread Index (ISI) and Build-up Index (BUI) combinations that yield active crown fires in the C3 fuel type; and c) that the average fire size (Table 16) is achieved. Burn probability (where mapped in following figures) was displayed as the ratio of burn probability of any given pixel compared to the mean burn probability of the modeled landscape (Table 6), i.e. if the mean burn probability of the total landscape is .05, and a given location has a burn probability of .10, it is considered 2x as likely to burn as the mean landscape, likewise if a given location has a burn probability of .025, it is -2x (or twice as likely not to burn). Burn probability has also been mapped by season to show variations in areas due to phenological fuel conditions (i.e. green versus cured grass, or leafless vs leaf-on aspen) and to account for the effect of "turning off fire" on parts of the landscape in spring for snow-cover .

Table 16. Average and maximum landscape burn probability (%) for Banff, Yoho and Kootenay National Parks (BYK), Jasper National Park (JNP), Waterton-Lakes National Park (WLNP) and Riding Mountain National Park (RMNP). BYK National Parks spring was modeled separate to include snow cover reducing the area available for burning. WLNP was modelled pre and post Kenow (2017) wildfire.

	BYK		JNP		WLNP		RMNP
Burn Probability (%)	Spring	Summer	Beetle	No Beetle	Pre-Kenow	Post-Kenow	
Landscape mean	0.102	0.096	0.041	0.016	0.625	0.725	0.199
Maximum	2.898	1.267	1.840	1.198	2.519	2.985	0.876
Burned Area (ha)							
Mean	3,972	3,744	1,608	515	1,508	1,472	1,328
Min-Max	3-83,650	3-154,617	3-149,468	3-66,439	1-82,575	2-75,818	0-99,001

Banff – Yoho – Kootenay National Parks

The part of the landscape with the highest burn probability in spring is just outside the park to the East (Figure 19) in the Ghost-Waiparous landscape, where it is was 3× greater than the landscape average. In summer, this area was 3× greater than the landscape average as was the area in and around Lake Louise. Within the boundaries of the park itself, fire intensity in spring and summer was highest in valley bottoms where forest cover was mostly coniferous, and in spring when the open grasslands are cured and conducive to rapid fire spread (Figure 20). Except for the Bow Valley, most of Banff National Park is unburnable in the early spring due to snow cover, however, this assumes average snowpack conditions, and in years with early melt or low snow cover this would change the picture. Many of the other valleys also can be clear of snow in the early spring (see the Spring Fire Intensity panel of Figure 20), which can lead to some high intensity fires, however the isolated nature of many of these valleys leads to very low likelihood of fire occurring in, or spreading from these locations at this time of year.

Summer hazard (the combination of fire likelihood and intensity) is highest in the Lake Louise region, and Saskatchewan Crossing areas within the Park boundaries (Figure 21 and Figure 22). However, these areas still have lower hazard than the Ghost-Waiparous just outside the Park. In the spring, fire hazard is highest in a small pocket around Lake Louise, and again outside the Park in the Ghost-Waiparous (Figure 21 and Figure 22). Mean fire intensity is mostly within Intensity Class (IC) IV (2,000-4,000 kW/m) during the spring season but this rises to IC V and VI during the summer. Figures 23-25 show relative burn probability in BYK broken down by finer seasonal delineations.

Summer hazard is higher around the town sites than it is during the spring conditions (Figure 22). The areas around Lake Louise are of high intensity and probability in the spring as well as the summer, however in the summer a larger part of the valley is of high intensity and probability, which is indicative of the potential of larger fires to occur. The area surrounding Field in Yoho National Park increases in fire intensity during the summer, while the probability remains moderate. The town of Banff, however, increases from low-probability/low-intensity in spring to low-probability/high-intensity in summer (Figure 22). The town site of Banff is has its highest burn probability in early and late fall (Figure 22) when grass curing is high and weather

conditions are conducive to more rapid and intense fire behaviour, while Lake Louise is at high risk from early summer through late fall (Figure 22). The majority of Kootenay National Park has a considerably low BP relative to Banff and Yoho.

The landscape immediately surrounding the town of Banff (Figure 26**Error! Reference source not found.**) shows that summer has a considerably higher BP than spring, and much of this area is to the east of the town site, but there are pockets of high BP scattered within the town and on all sides. Summer shows more areas with higher intensity fire than spring (Figure 27), and if fire were to occur under these conditions (Intensity Class VI), fire would be virtually uncontrollable. Fires in spring that are in the immediate vicinity of the town tend to burn at lower intensity (Intensity Class IV, which permits direct action, or Intensity Class V, which permits indirect attack). The hazard maps (Figure 28), show the distribution of hazard immediately surrounding the town in spring and summer fuel conditions. The town of Canmore shows similar BP (Figure 29) and fire intensity distribution (Figure 30), however Canmore faces higher spring hazard than summer (Figure 31) whereas Banff has a higher summer hazard than spring. The town of Field has very low BP (Figure 32) relative to the rest of the BYK landscape, with a slightly higher spring BP than it does in summer due to grassy fuels, however there is little difference in spring vs summer intensity (Figure 33). The overall hazard surrounding Field is relatively low (Figure 34). Lake Louise townsite, on the other hand, has an elevated BP (Figure 35) and hazard (Figure 37) relative to the rest of the landscape in spring, and a very high BP and hazard in the summer. Like Field, there is little difference in intensity in spring vs summer surrounding Lake Louise (Figure 36).

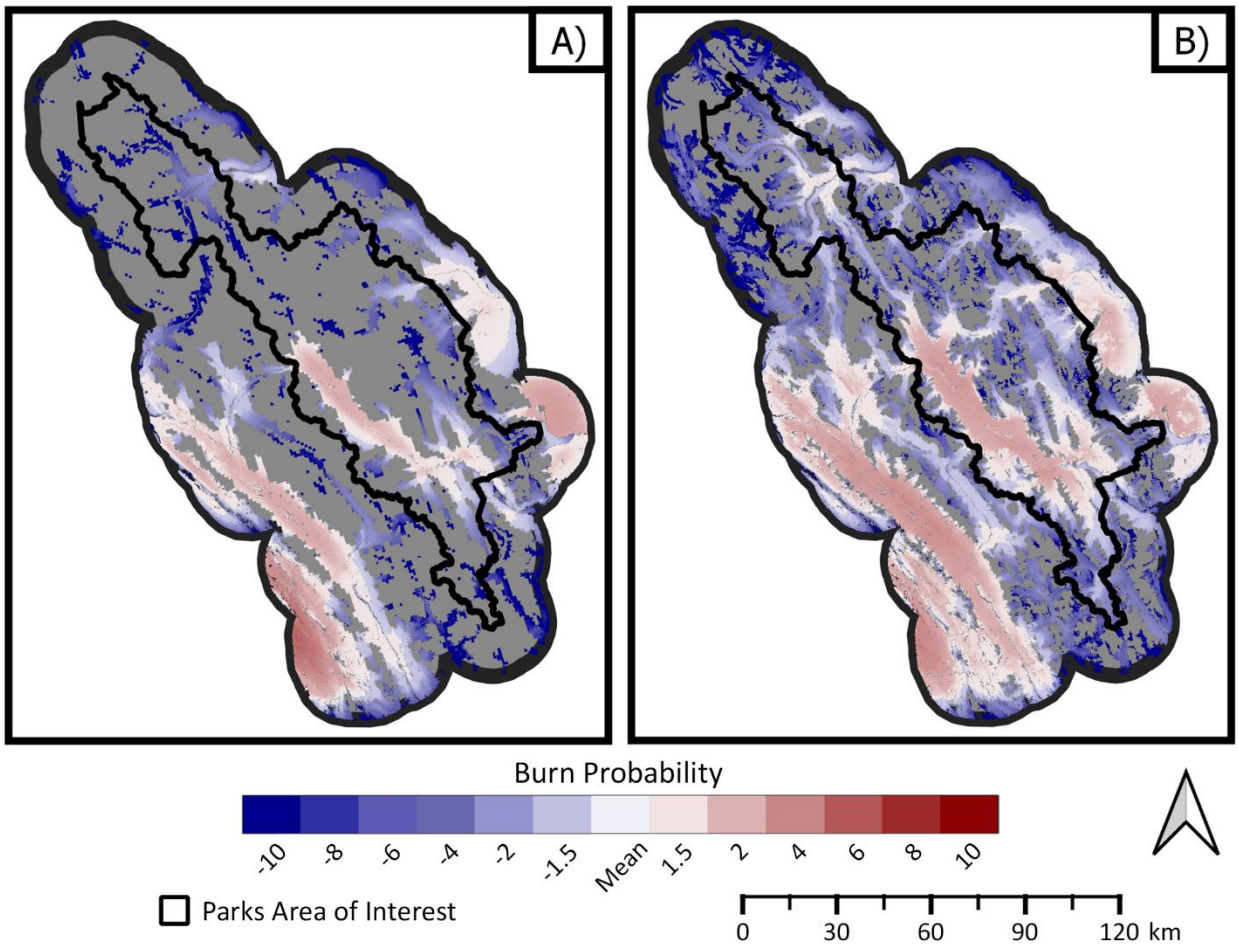

Figure 19. A) Spring and B) Summer burn probability in Banff, Kootenay and Yoho National Parks. Mean spring and summer landscape burn probability are 0.102% and 0.096% respectively.

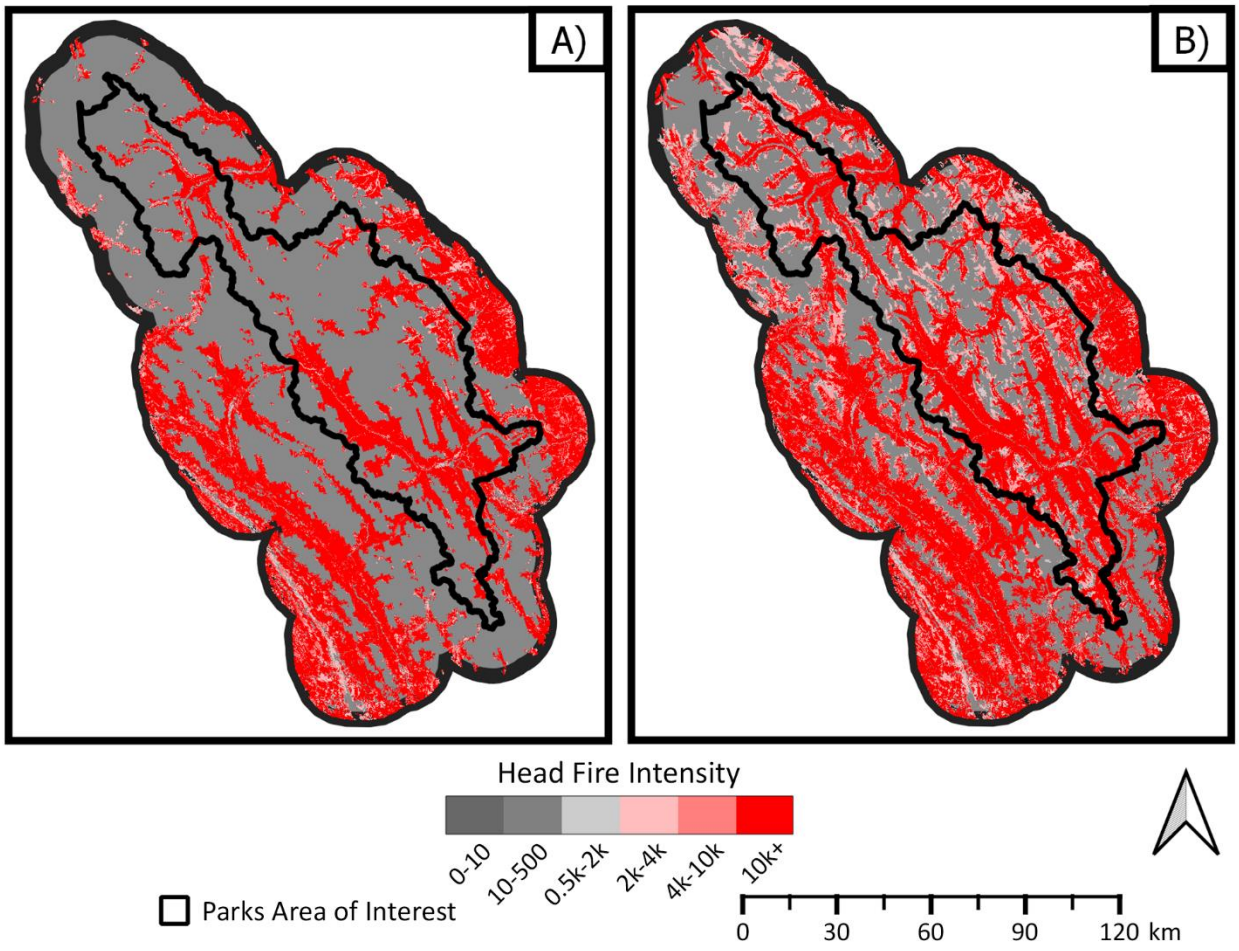

Figure 20. A) Spring and B) Summer fire intensity in Banff, Kootenay and Yoho National Parks.

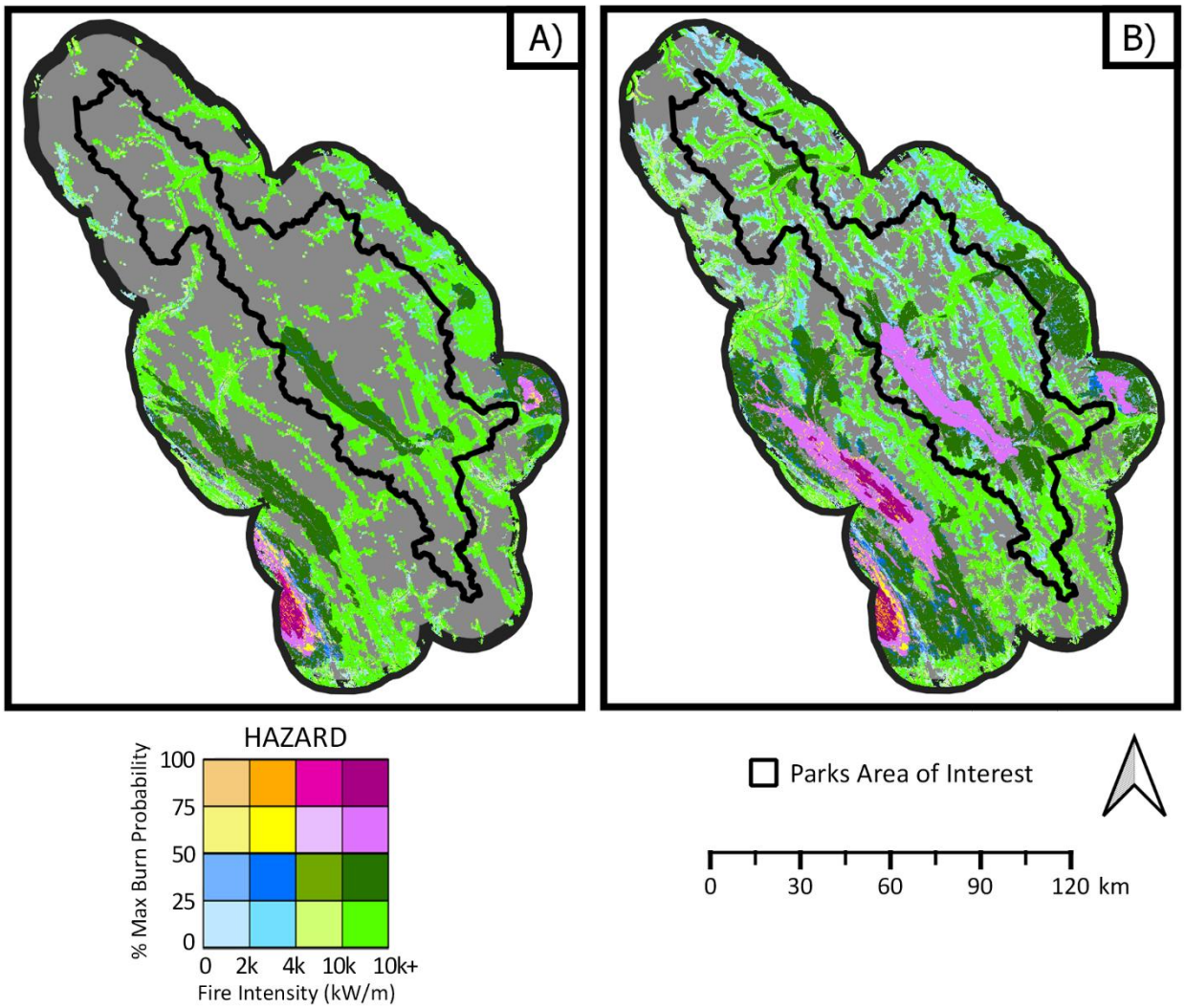

Figure 21. A) Spring and B) Summer wildfire hazard in Banff, Kootenay and Yoho National Parks.

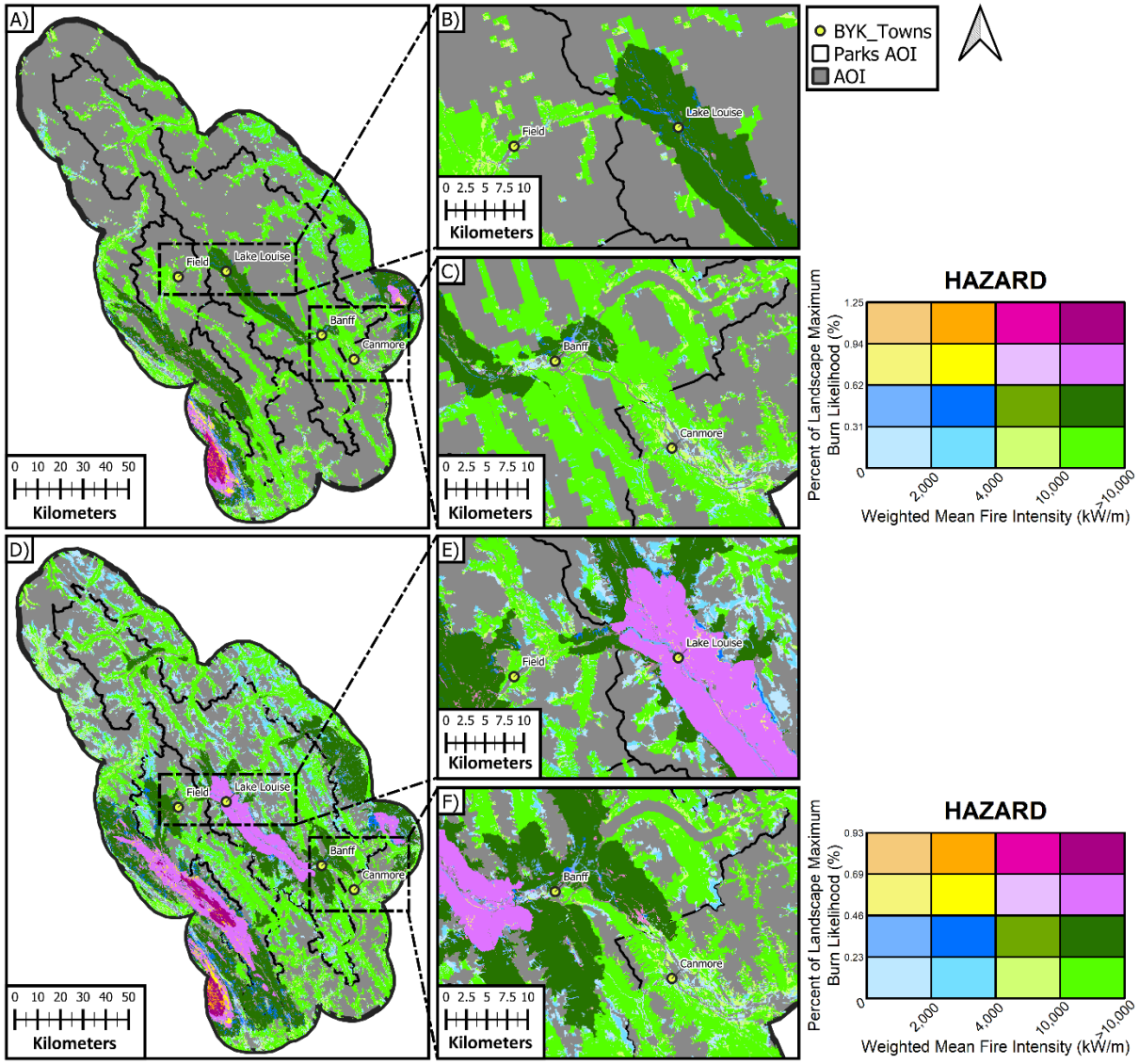

Figure 22. Wildfire hazard within Banff, Kootenay and Yoho National Parks (burn probability (%) and average fire intensity (kW/m)) for the A) spring (Apr. 1st – May 31st) and a closer look at B) Lake Louise and C) Banff and Canmore. D) Summer-fall (Jun. 1st – Sep. 30th) with a closure look at E) Lake Louise and F) Banff and Canmore. Note: burn likelihood scale is different between Spring and Summer.

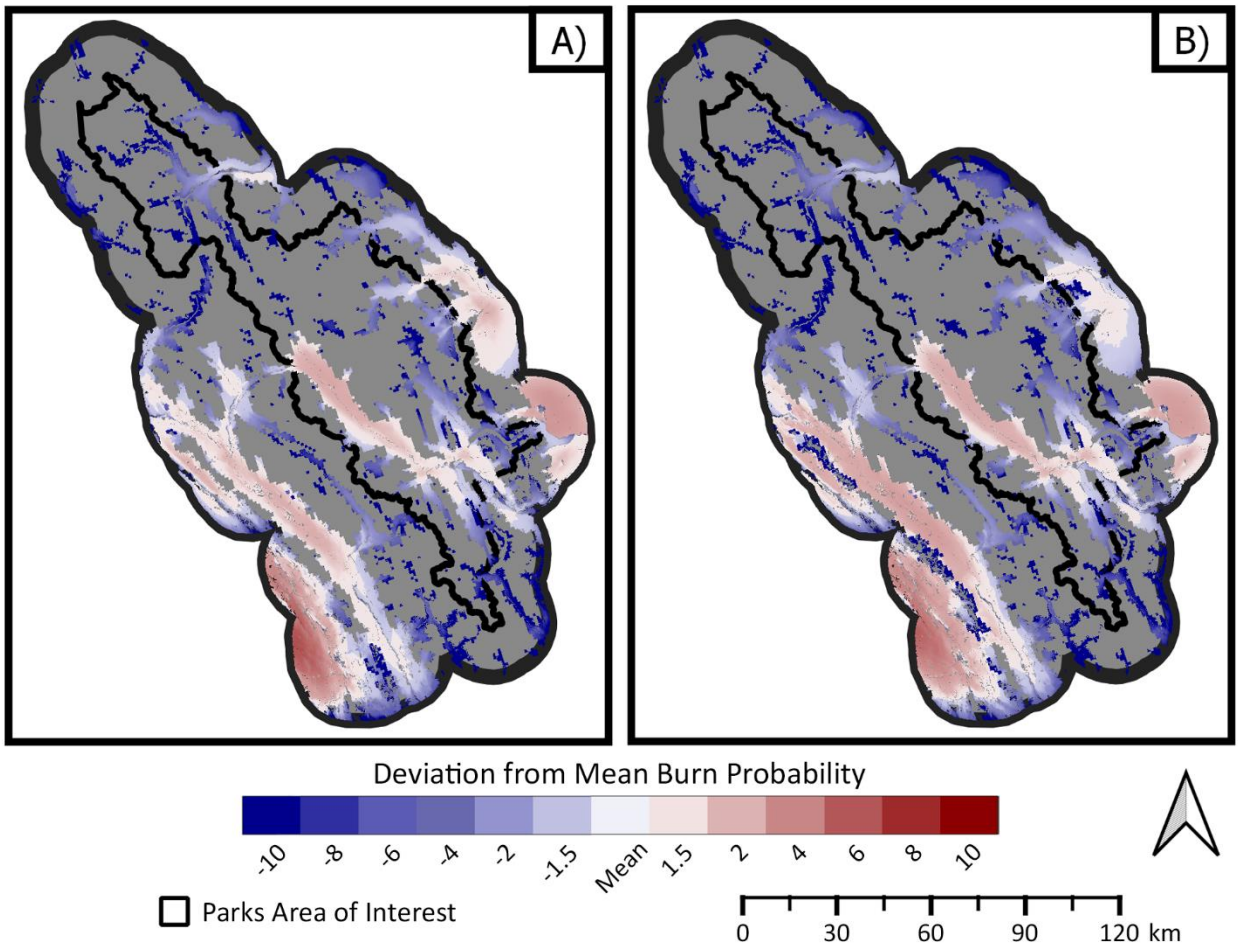

Figure 23. Burn probability for A) early (April 1st – April 30th) and B) late (May 1st – May 31st) spring.

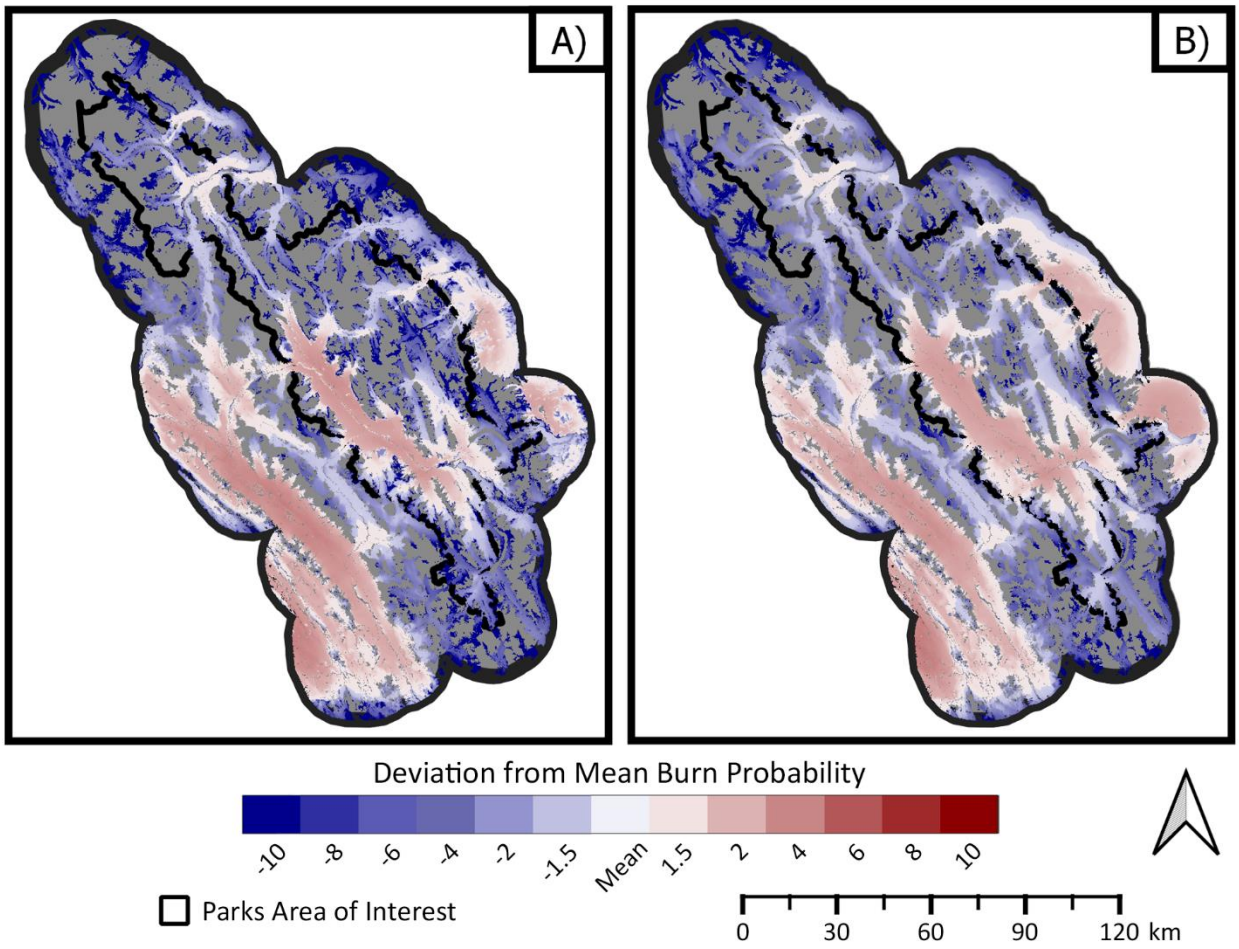

Figure 24. Burn probability for A) early (Jun. 1st – Jul. 31st) and B) late (Aug. 1st – Aug. 31st) summer.

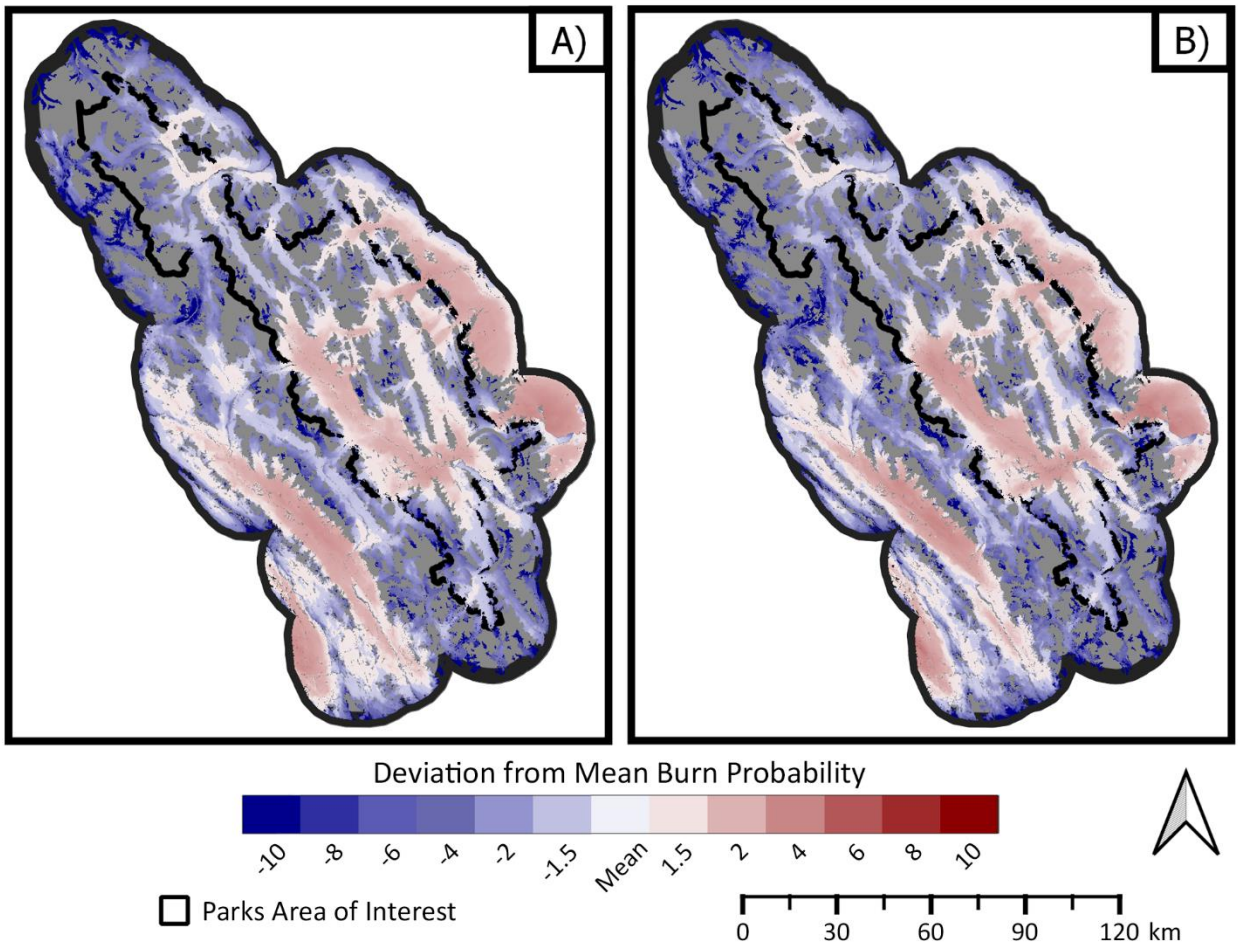

Figure 25. Burn probability A) early (Sep. 1st – Sep. 15th) and B) late (Sep. 16th – Sep. 30th) fall.

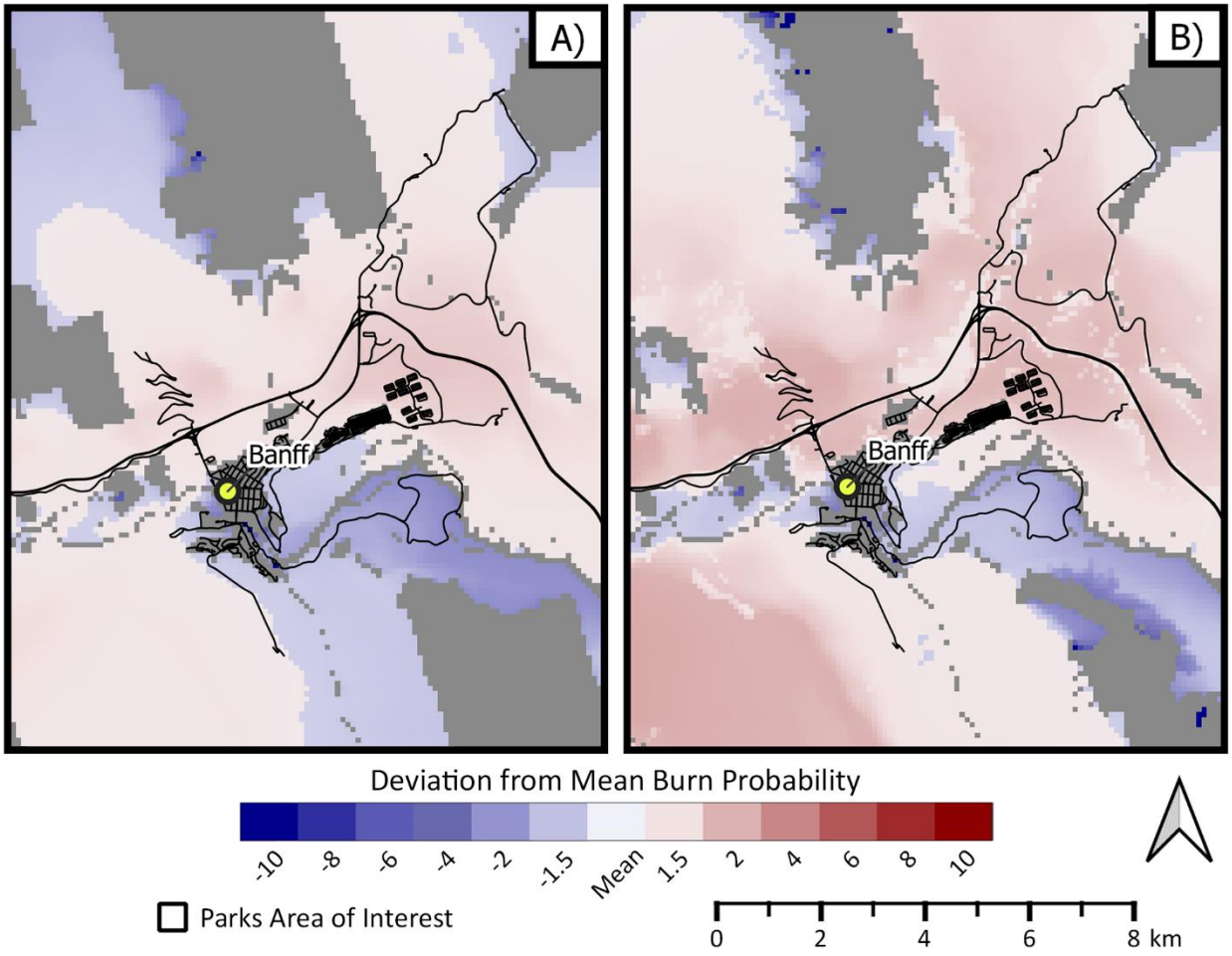

Figure 26. A) Spring and B) Summer burn probability surrounding Banff townsite. Mean spring and summer landscape burn probability are 0.102% and 0.096% respectively.

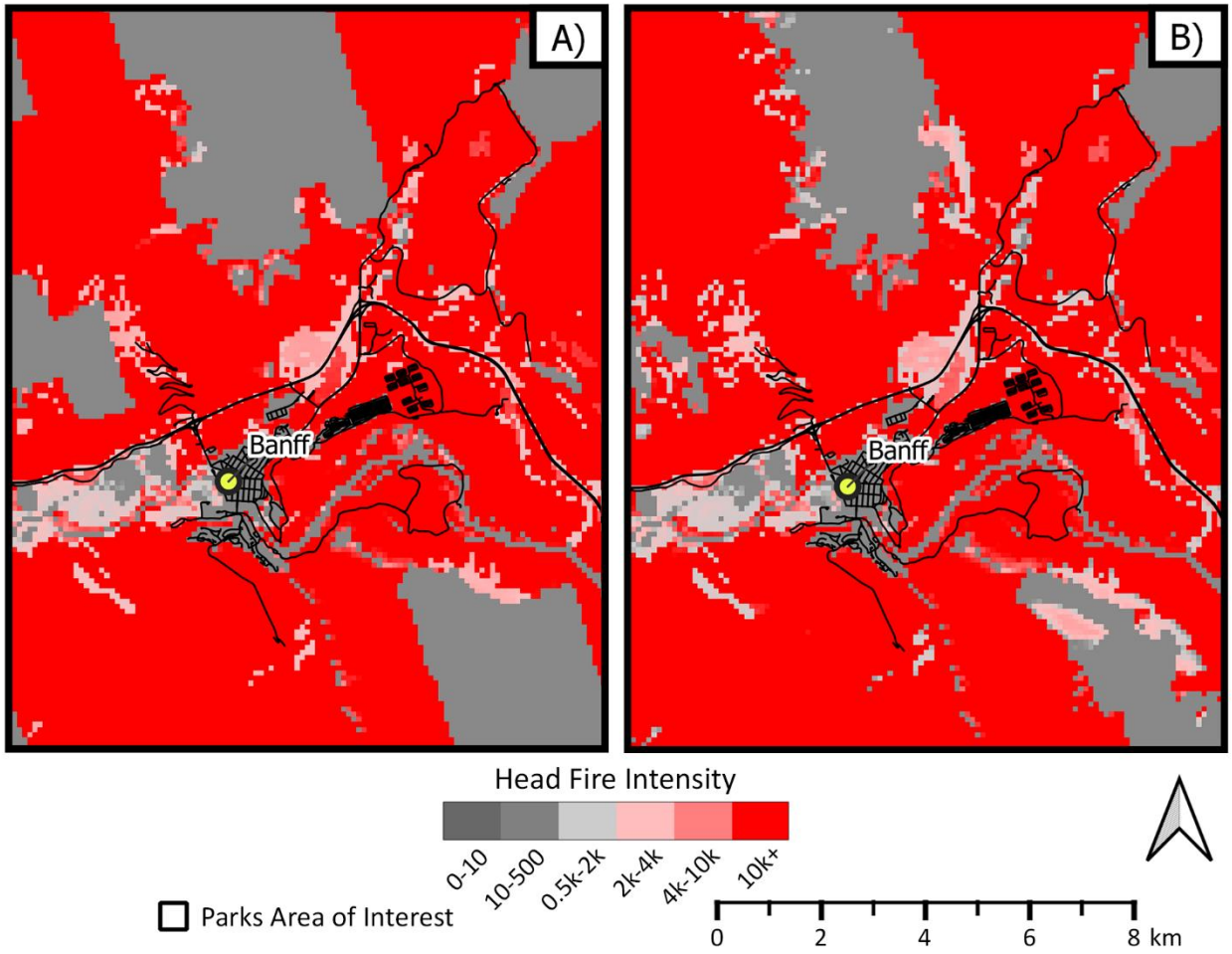

Figure 27. A) Spring and B) Summer fire intensity surrounding Banff townsite.

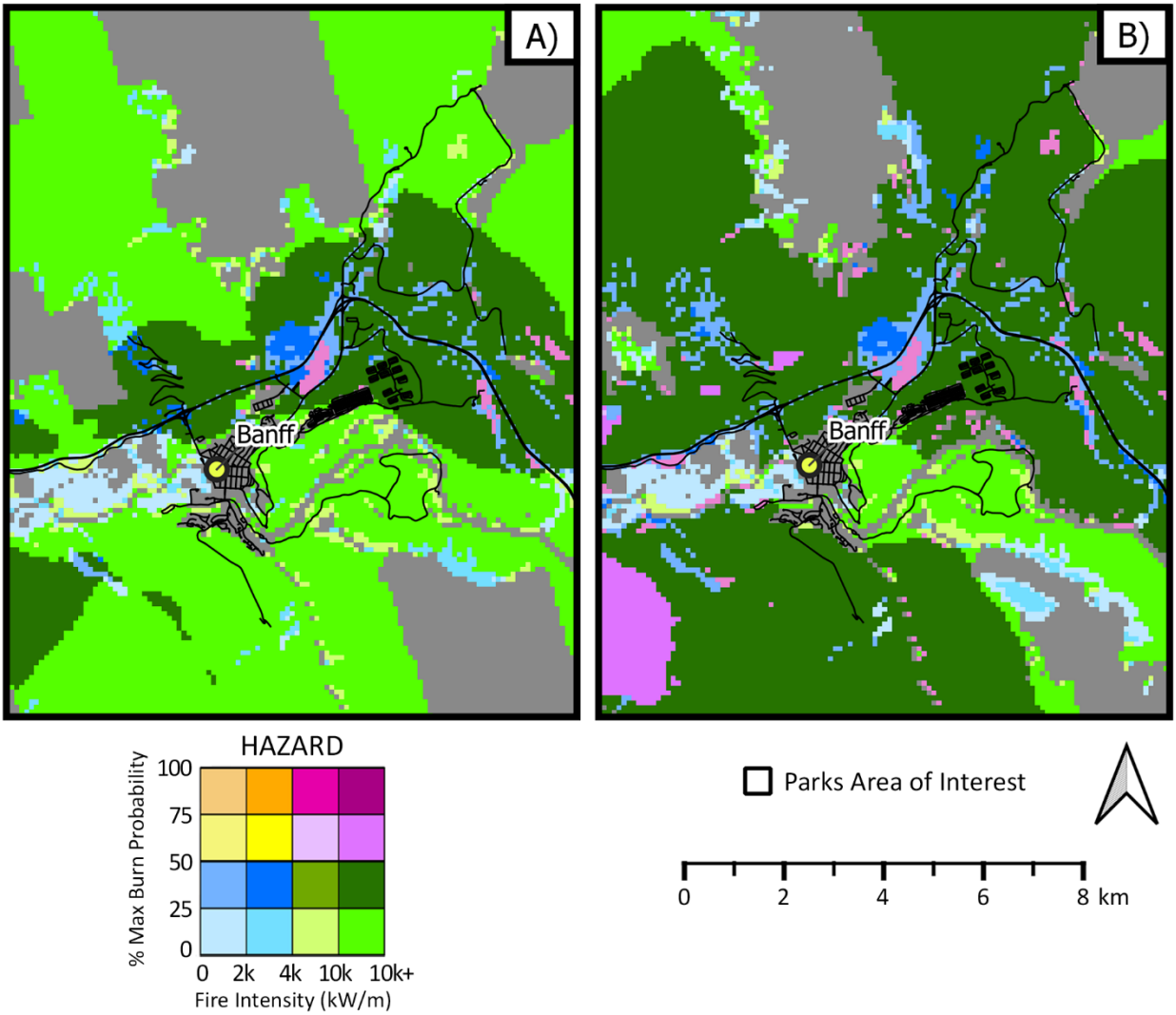

Figure 28. A) Spring and B) Summer wildfire hazard surrounding Banff townsite.

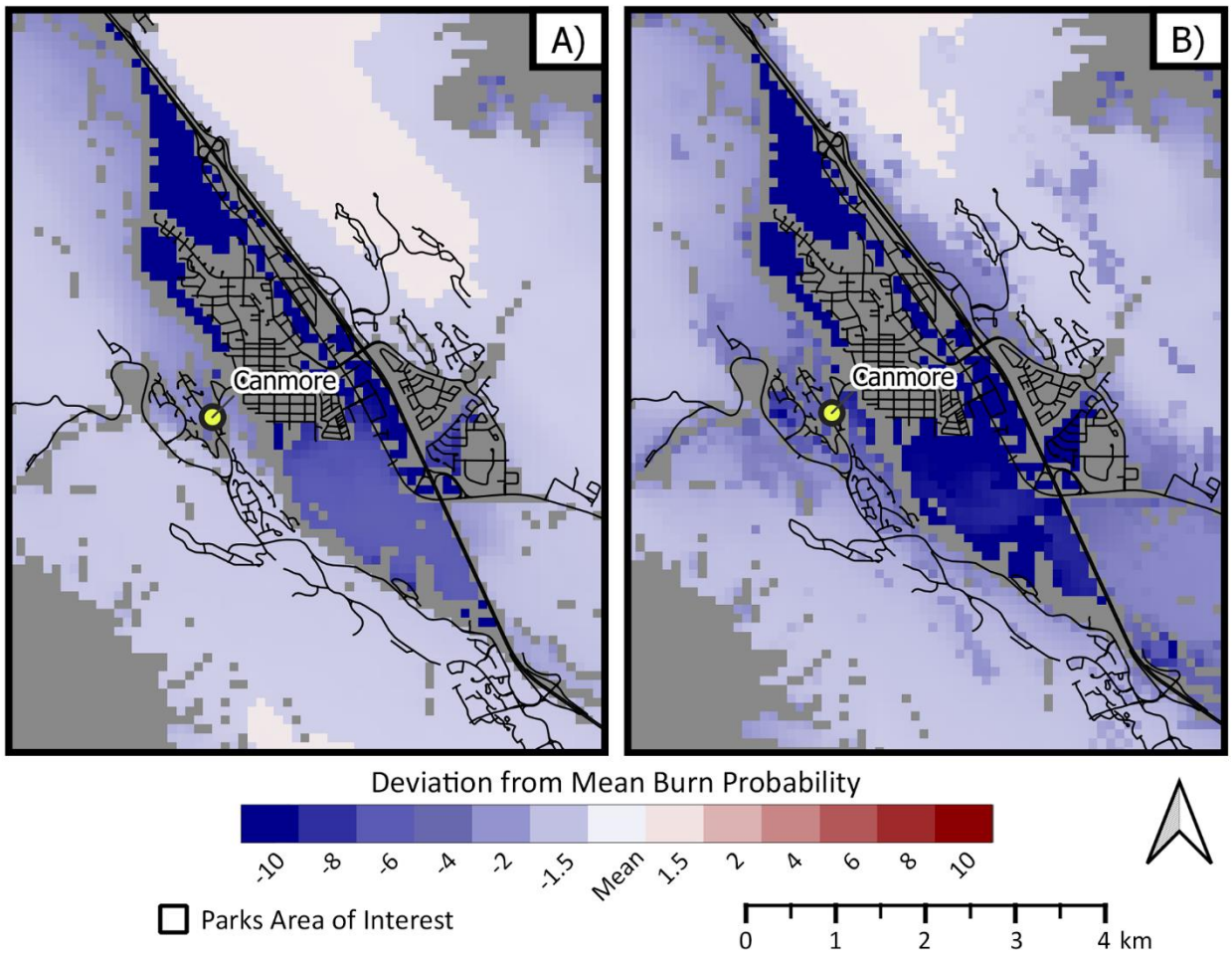

Figure 29. A) Spring and B) Summer burn probability around the townsite of Canmore. Mean spring and summer landscape burn probability are 0.102% and 0.096% respectively.

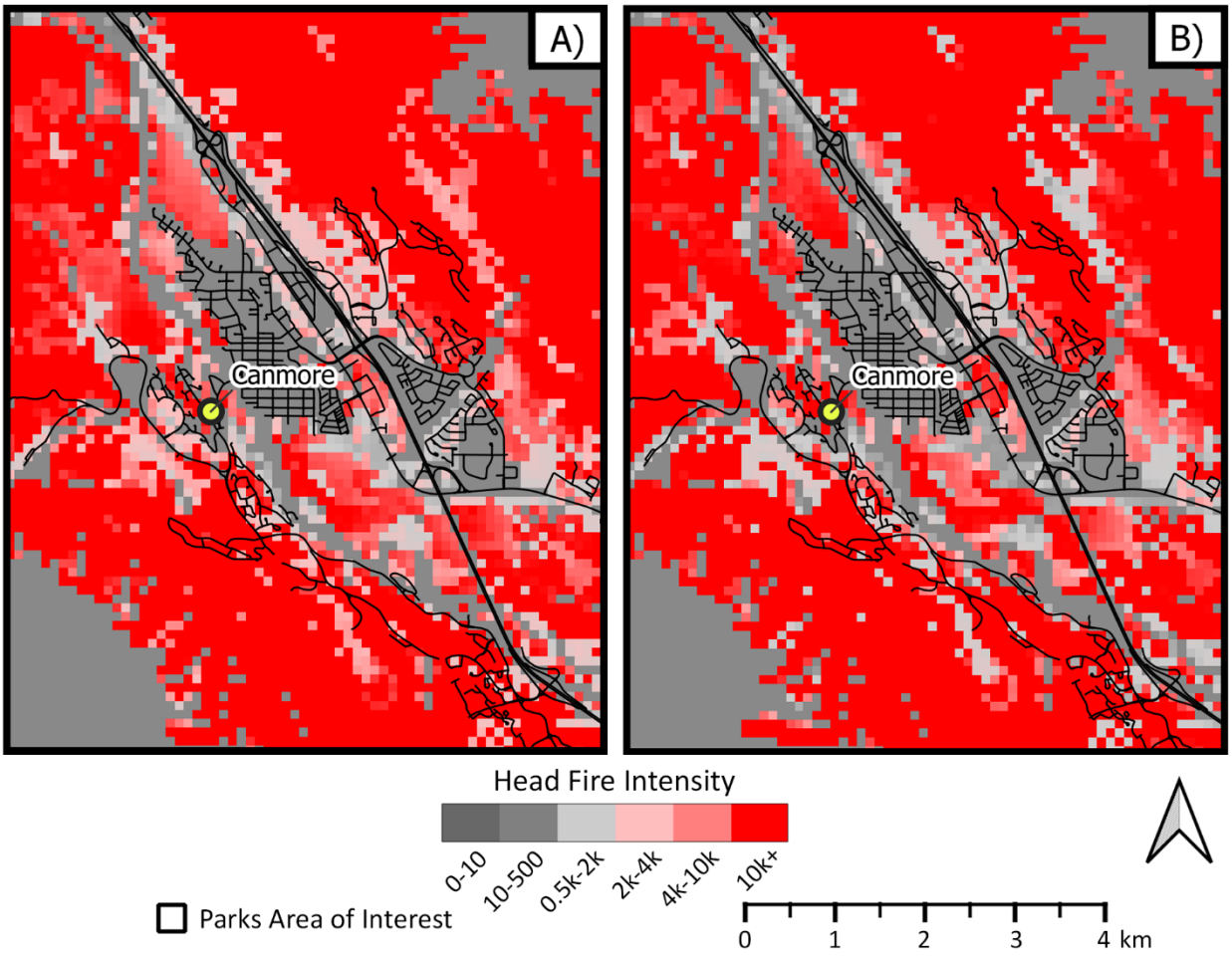

Figure 30. A) Spring and B) Summer fire intensity around the townsite of Canmore.

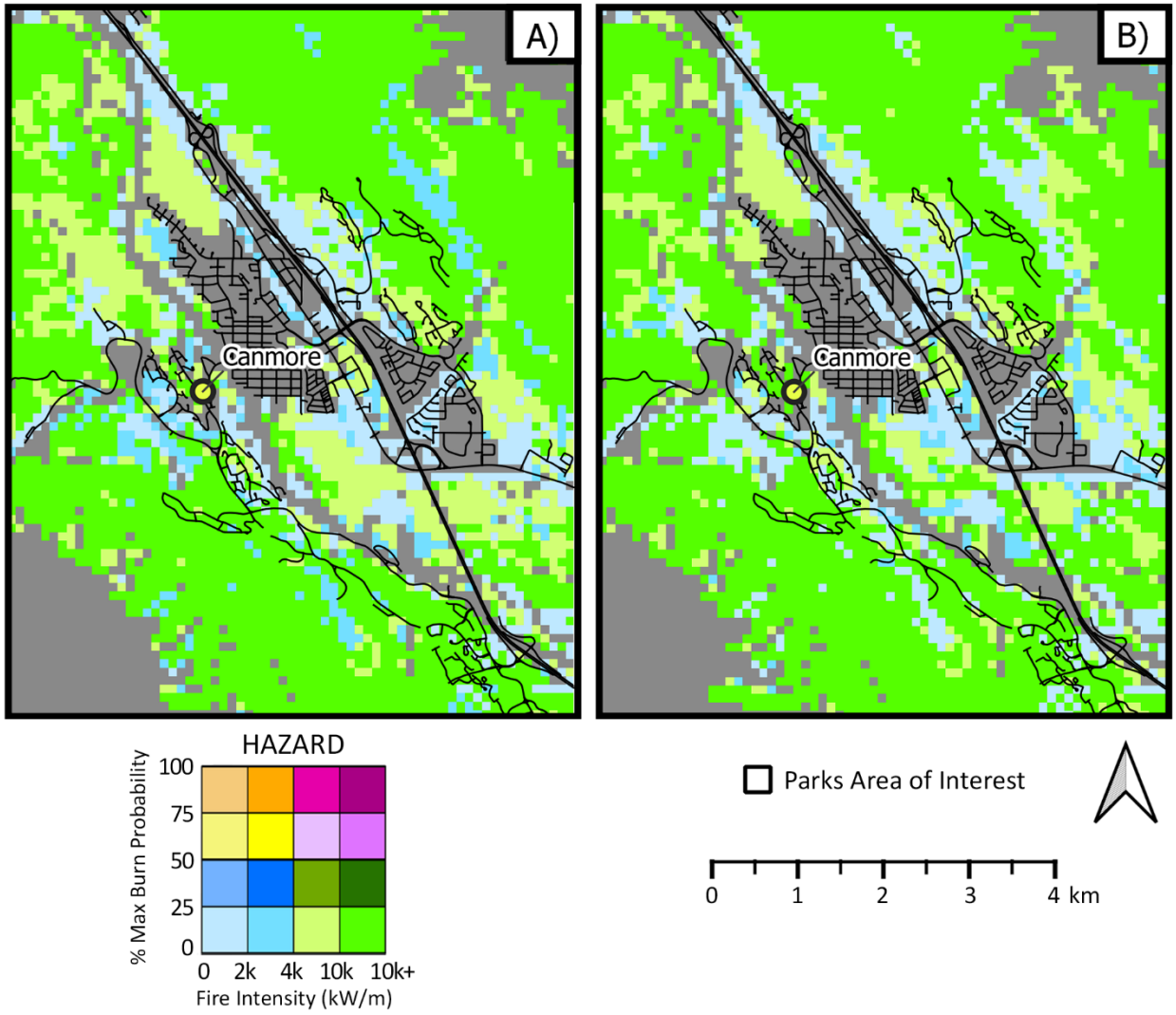

Figure 31. A) Spring and B) Summer wildfire hazard around the townsite of Canmore.

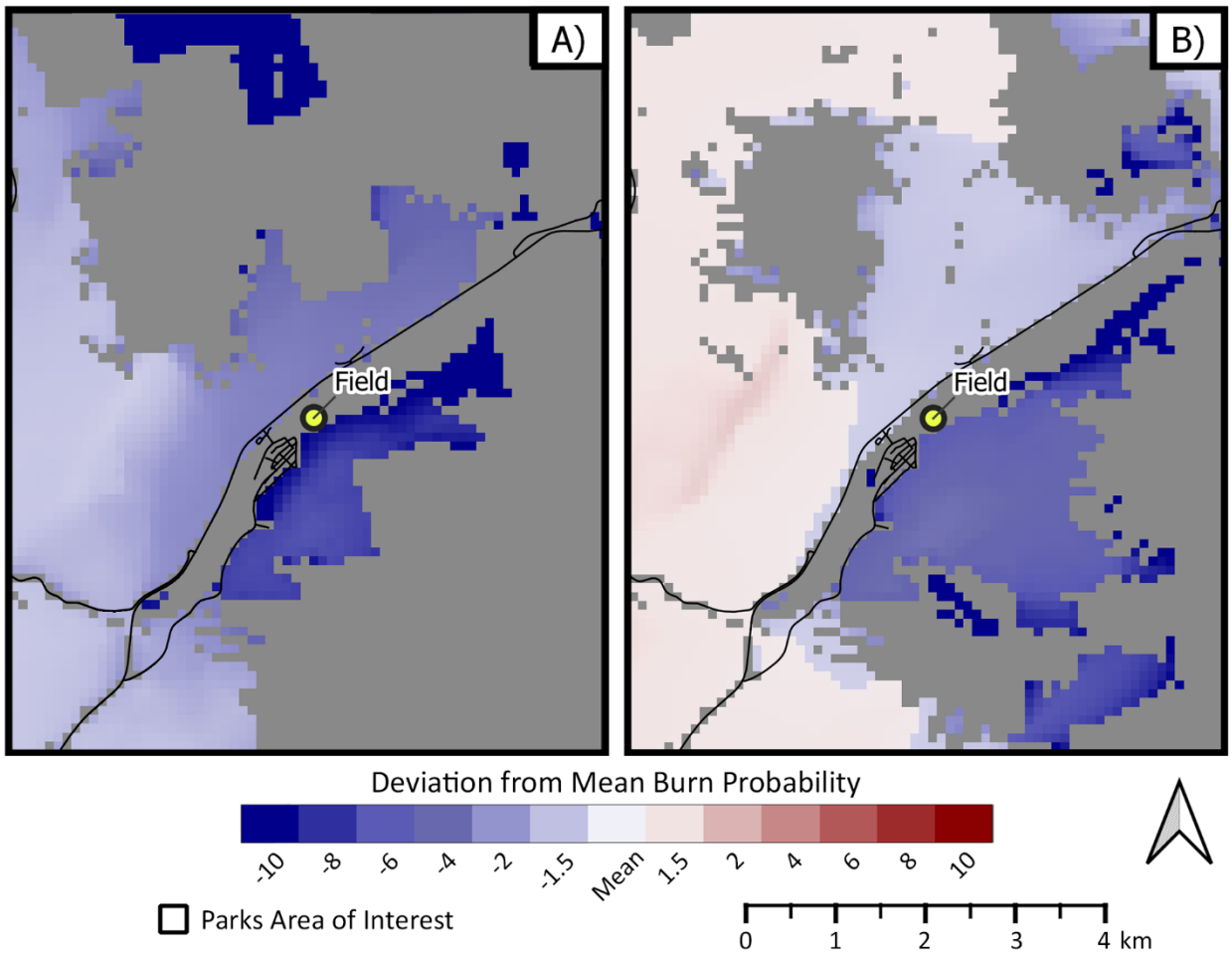

Figure 32. A) Spring and B) Summer burn probability surrounding Field. Mean spring and summer landscape burn probability are 0.102% and 0.096% respectively.

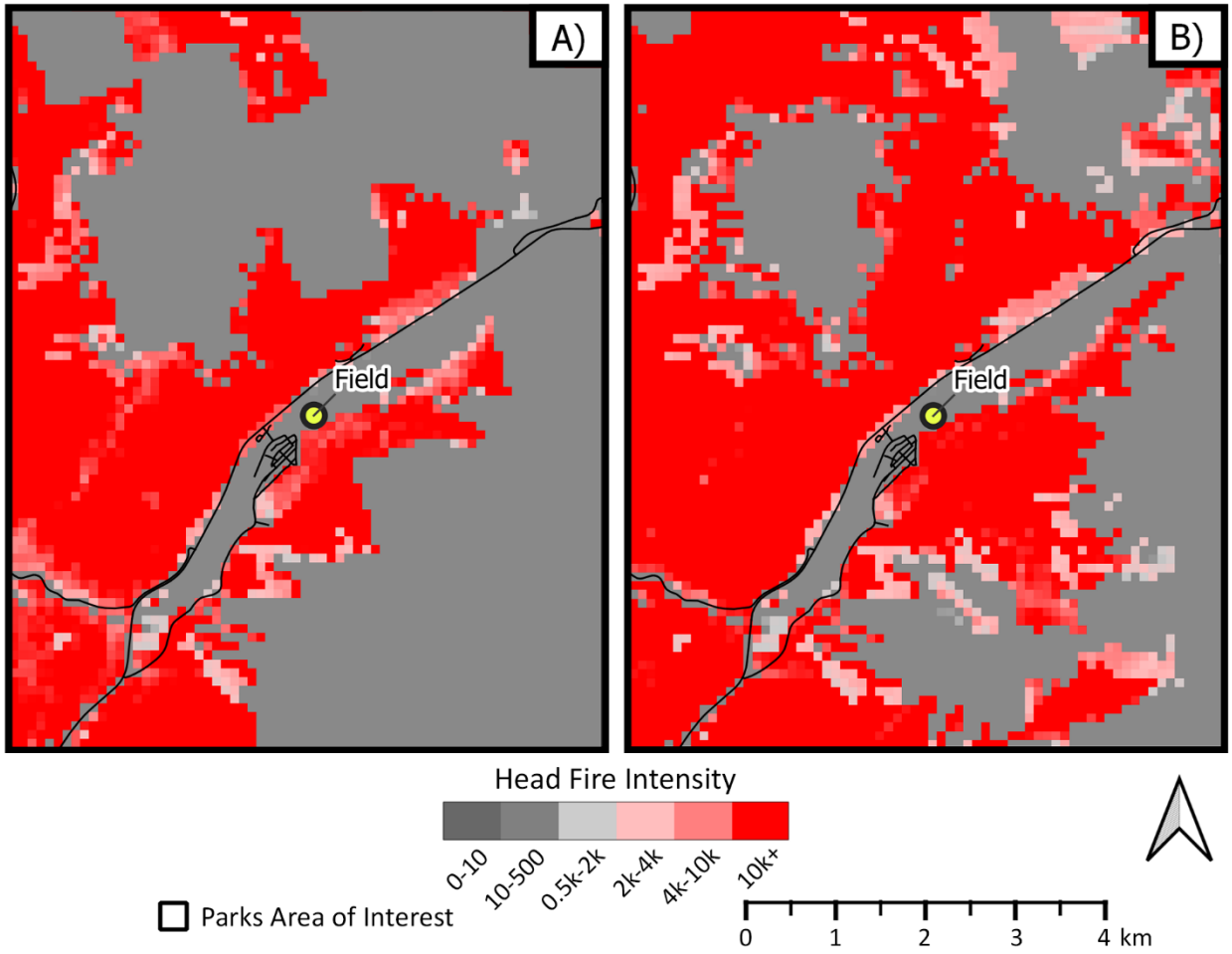

Figure 33. A) Spring and B) Summer fire intensity surrounding Field.

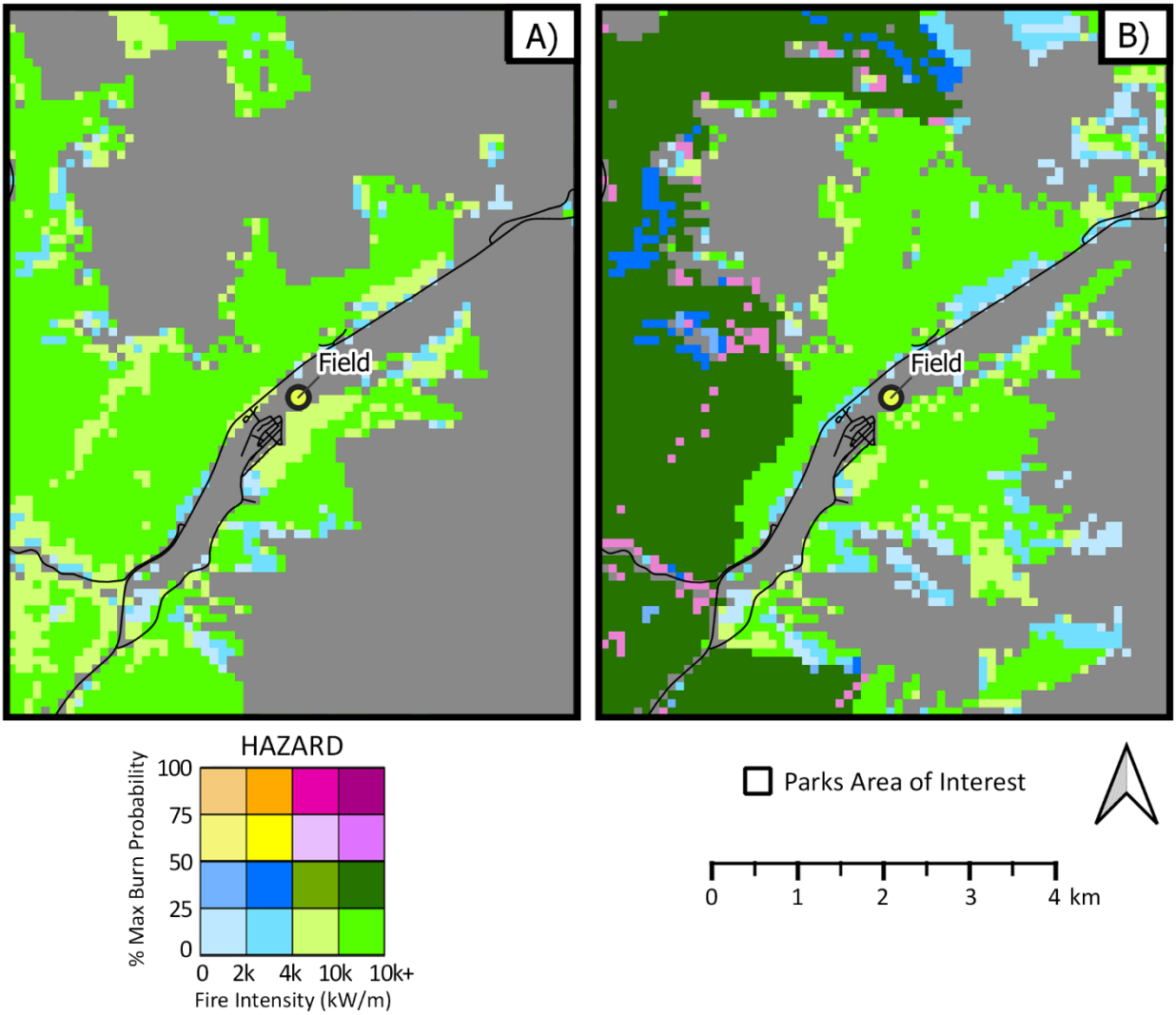

Figure 34. A) Spring and B) Summer wildfire hazard in Field.

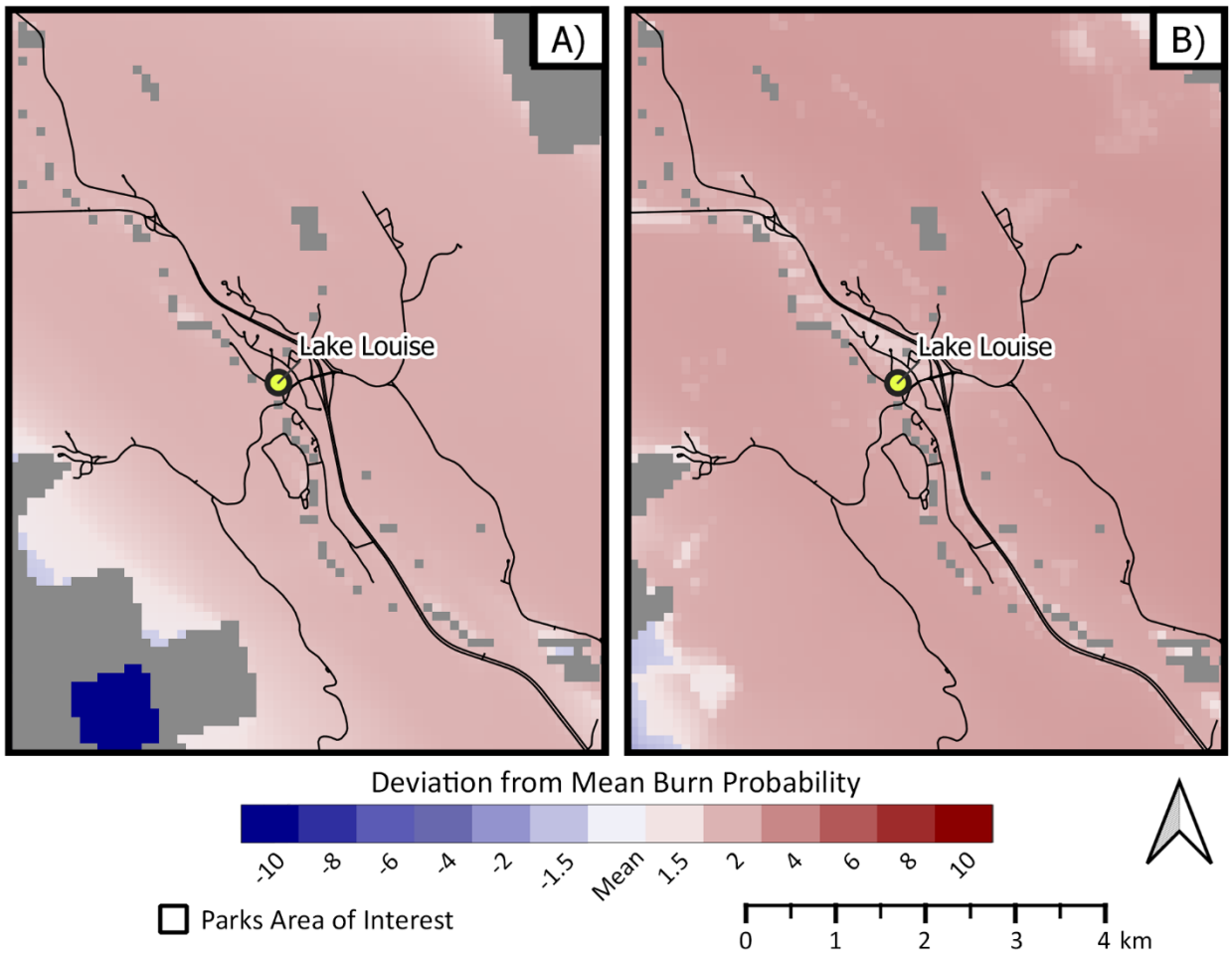

Figure 35. A) Spring and B) Summer burn probability around the townsite of Lake Louise. Mean spring and summer landscape burn probability are 0.102% and 0.096% respectively.

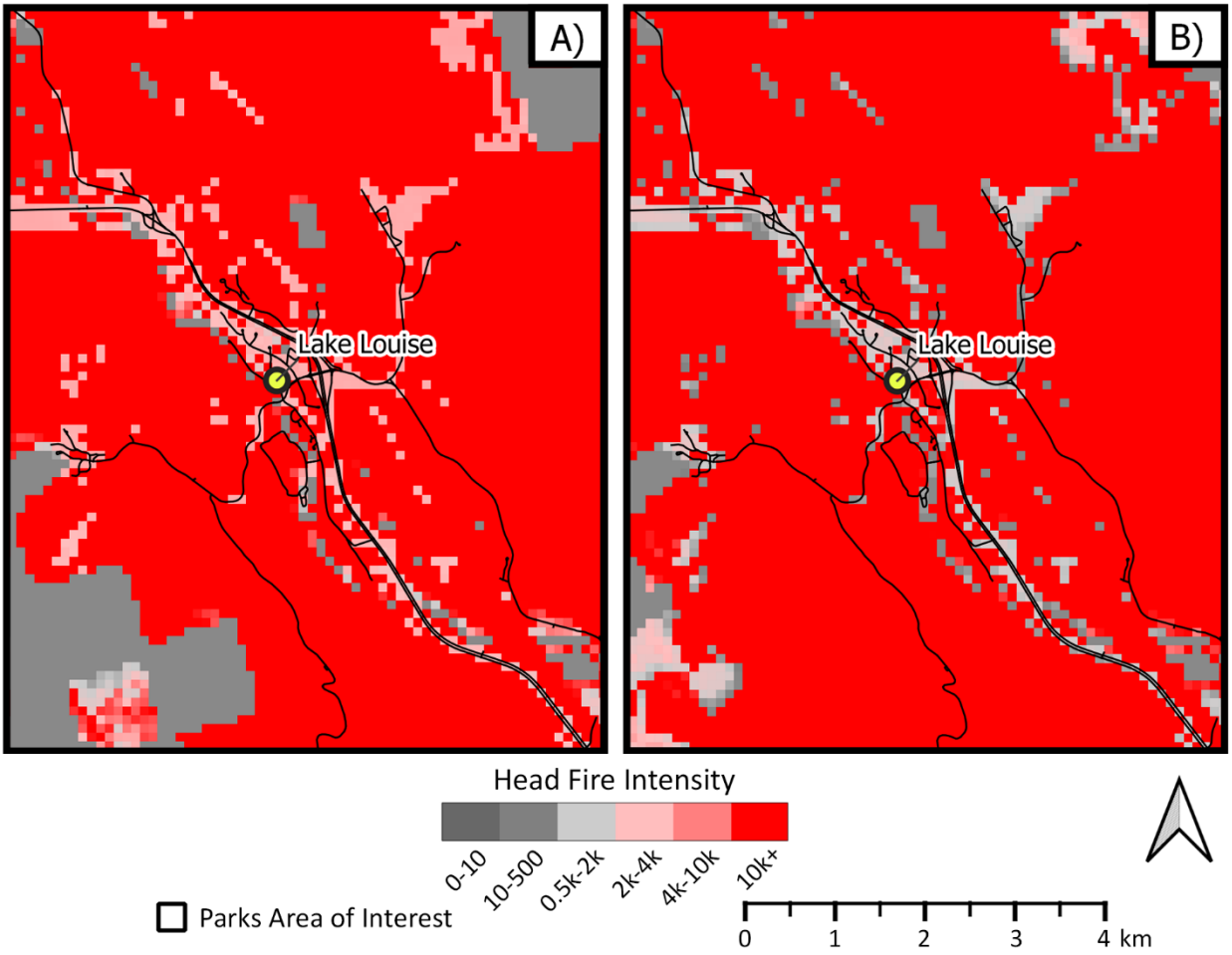

Figure 36. A) Spring and B) Summer fire intensity around the townsite of Lake Louise.

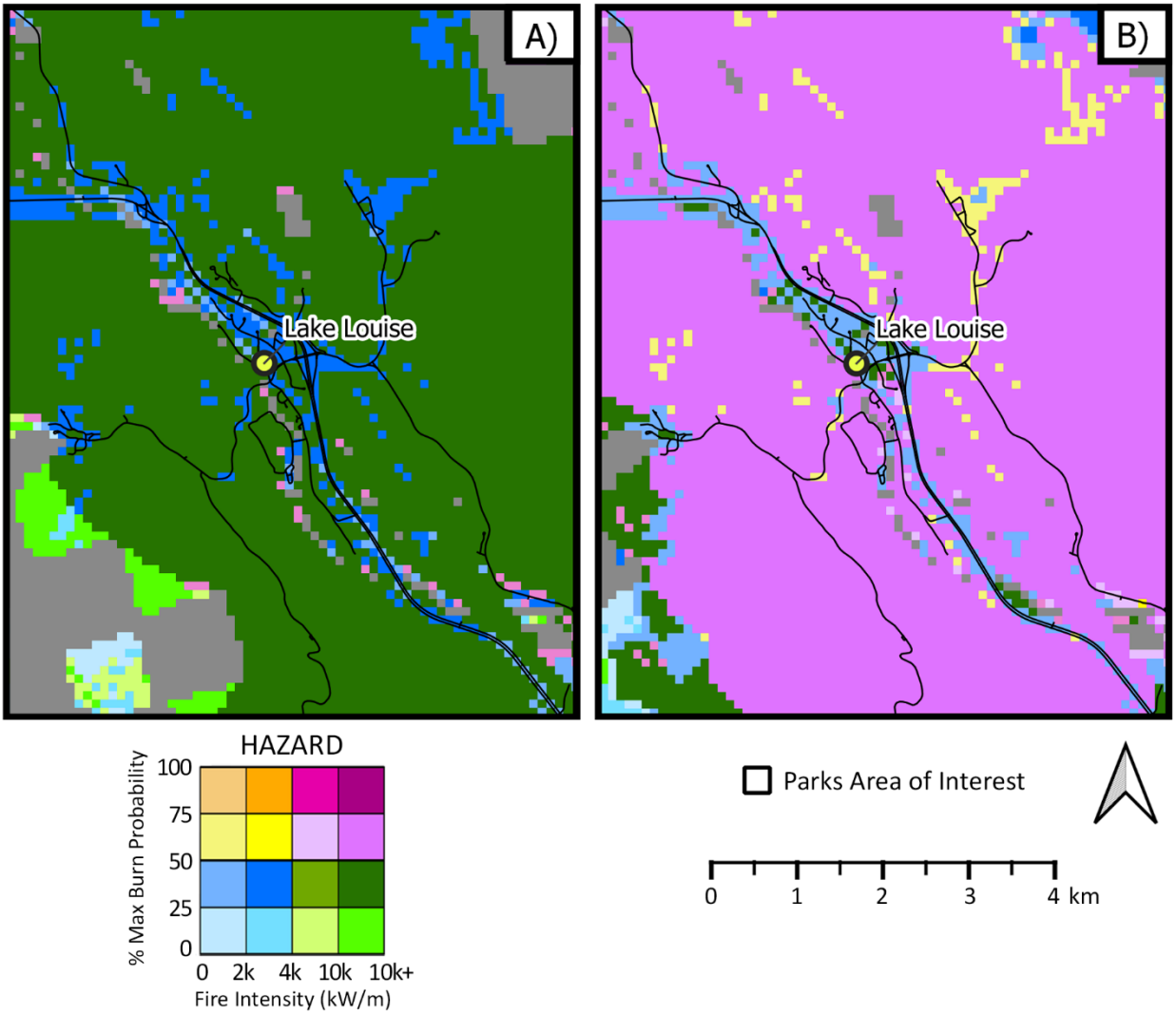

Figure 37. A) Spring and B) Summer wildfire hazard around the townsite of Lake Louise.

The fuel treatments in the immediate vicinity of the town of Banff have increased the BP, but the effects on burn probability, potential fire intensity, and hazard in all seasons is complex (Figure 38 through Figure 48). This modeling exercise has only begun to explore their effectiveness, and there are vital caveats associated with this in the discussion. The effect on BP is relatively small (Figure 38 and Figure 39), but we do see a larger change in hazard (Figure 40 and Figure 41), a full hazard class up from pre-management to current fuels in some locations, however these increases are sometimes offset with decreases elsewhere. The slight increases in BP (Figure 38 and Figure 39), intensity (Figure 40 and Figure 41) and hazard (Figure 42 and

Figure 43) are attributable to known weaknesses in the FBP fuel type system, and this issue will be described in depth in the discussion section.

We found a slight reduction in the size of the fireshed (Figure 44 and Figure 45) due to the fuel treatments, but the changes are subtle and driven by complex interplay of the various modeling parameters chosen to this point. Current work being led by Dr. Denys Yemshanov, with our participation is taking suppression activity into account and will be able to describe fuel management effectiveness in a more comprehensive manner in a later report. Figure 47 shows that the fuel treatments immediately surrounding Banff have increased the likelihood of burning by 1.1-1.5 times over the baseline value, but this increase does not take likely increases in suppression capabilities into account. The figures surrounding Banff were generated from a re-run scenario where only fires that intersected with fuel management treatments were simulated. This is a smaller subset from the broader landscape simulations, and as such some differences in burn probability are noticeable. Figure 48 demonstrates the relative change in burn probability when comparing the pre-treatment fuels to the current fuels. While some increases and decreases in burn probability can be seen this is largely a metric of the potential of a fire to spread and does not demonstrate the destructive potential of that fire. Figure 49 shows the change in head fire intensity class from pre-treatment fuels to the current fuel situation. Much of the fuel-treatment zone shows no effect on fire intensity (more on this in the discussion), but a significant portion of the area has had largely decreased fire intensity, which shows whether fuel treatment fuel trajectories have resulted in readily suppressible wildfire. Source-sink dynamics (Figure 50, Figure 51, and Figure 52) show that the largest valleys are both the largest sources and sinks of fire on the landscape, and that most of the region burns under larger fires than are generated from the same locations.

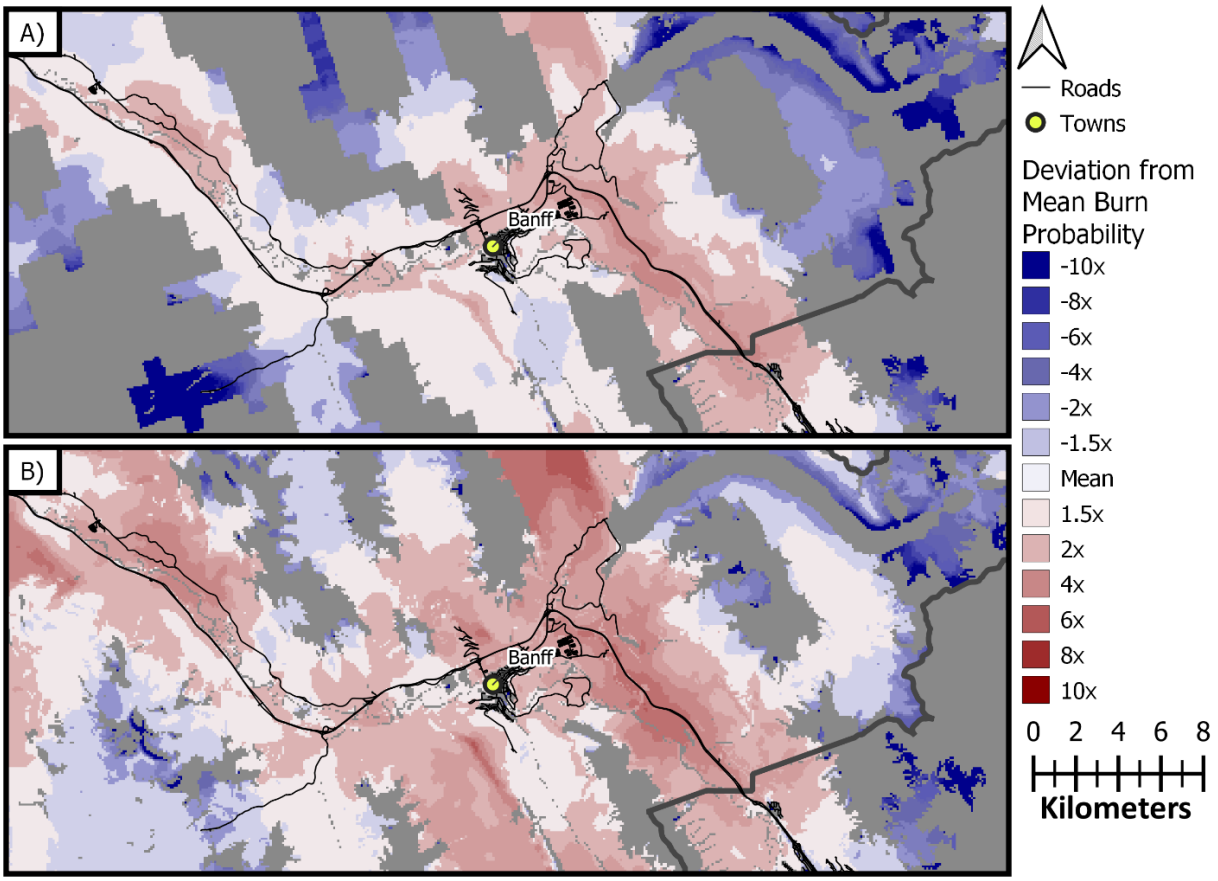

Figure 38. A) Spring (Apr. 1st – May 31st) and B) Summer (Jun. 1st – Sep. 30th) burn probability of the current landscape. Landscape mean burn probability is 0.062% and 0.070% respectively.

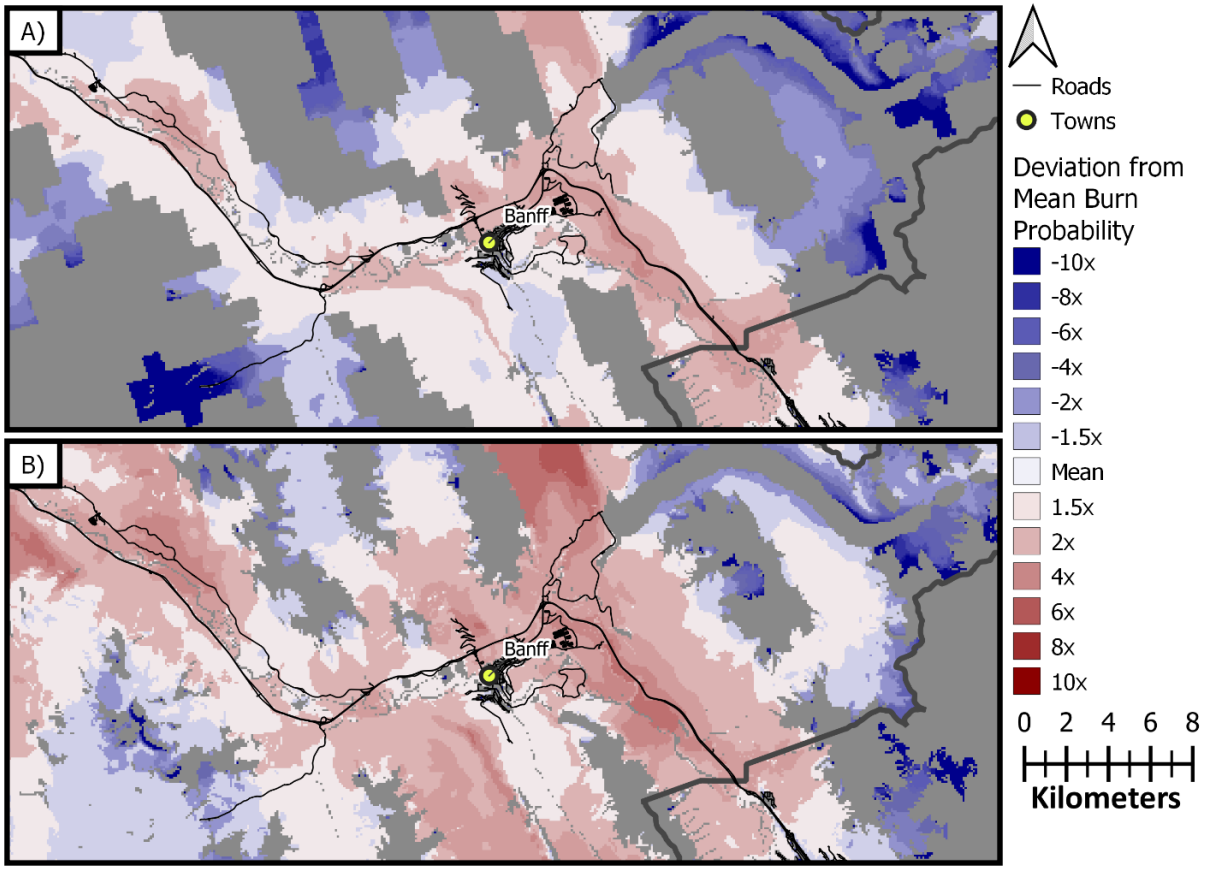

Figure 39. A) Spring (Apr. 1st – May 31st) and B) Summer (Jun. 1st – Sep. 30th) burn probability of the no-fuels-management landscape. Landscape mean burn probability is 0.042% and 0.070% respectively.

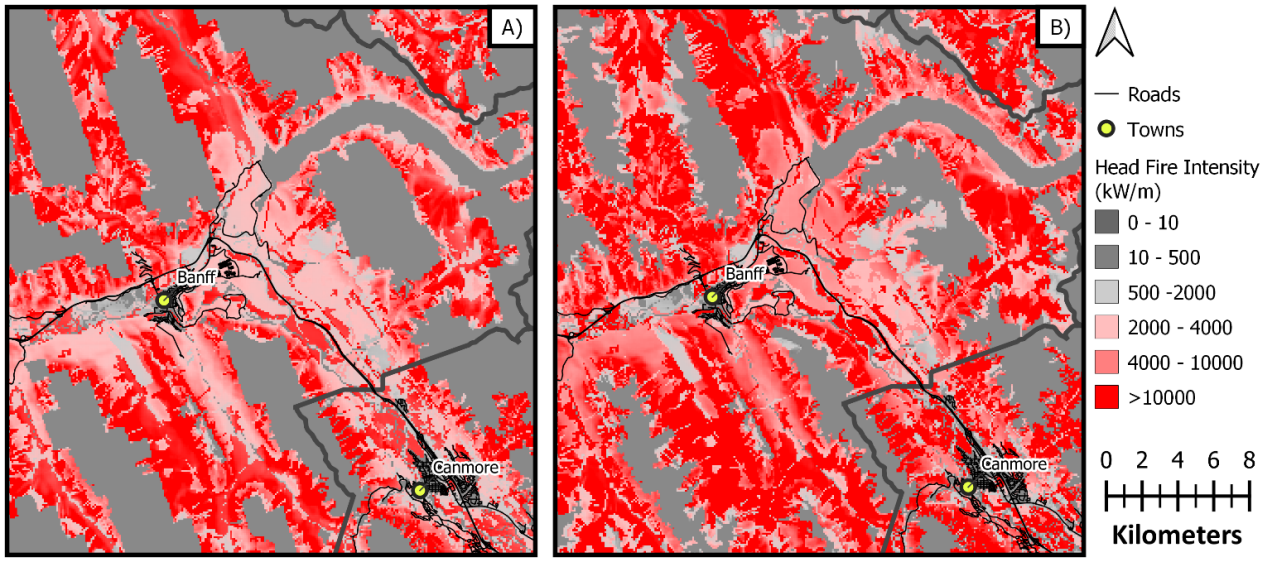

Figure 40. A) Spring (Apr. 1st – May 31st) and B) Summer (Jun. 1st – Sep. 30th) fire intensity (kW/m) on the current fuels landscape.

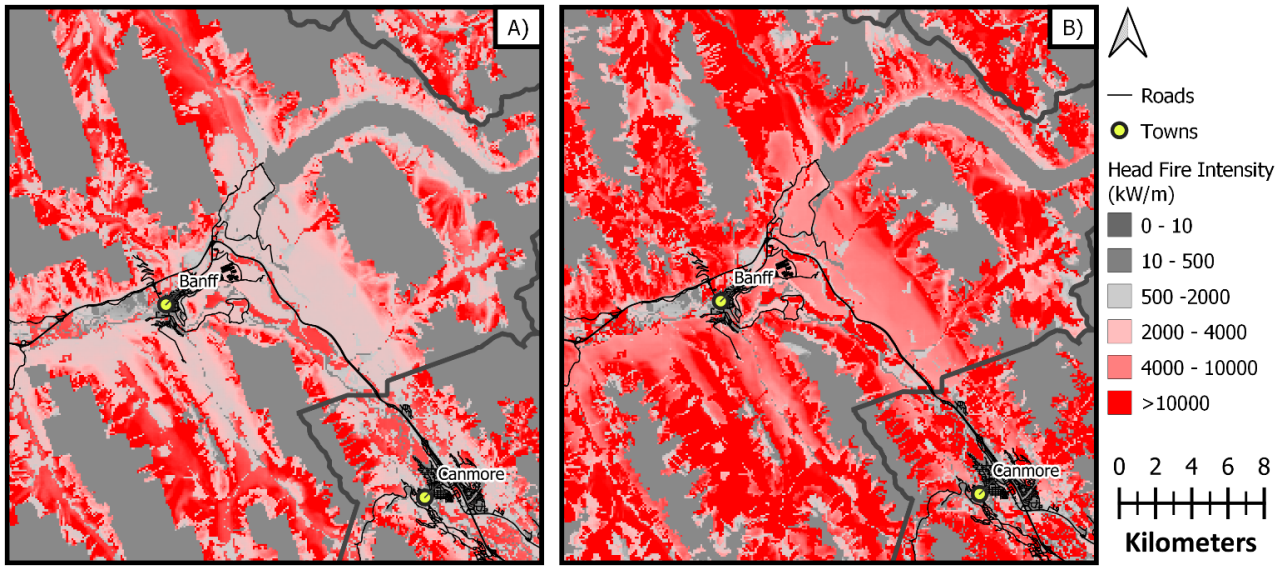

Figure 41. A) Spring (Apr. 1st – May 31st) and B) Summer (Jun. 1st – Sep. 30th) fire intensity (kW/m) on the no-fuels-management landscape.

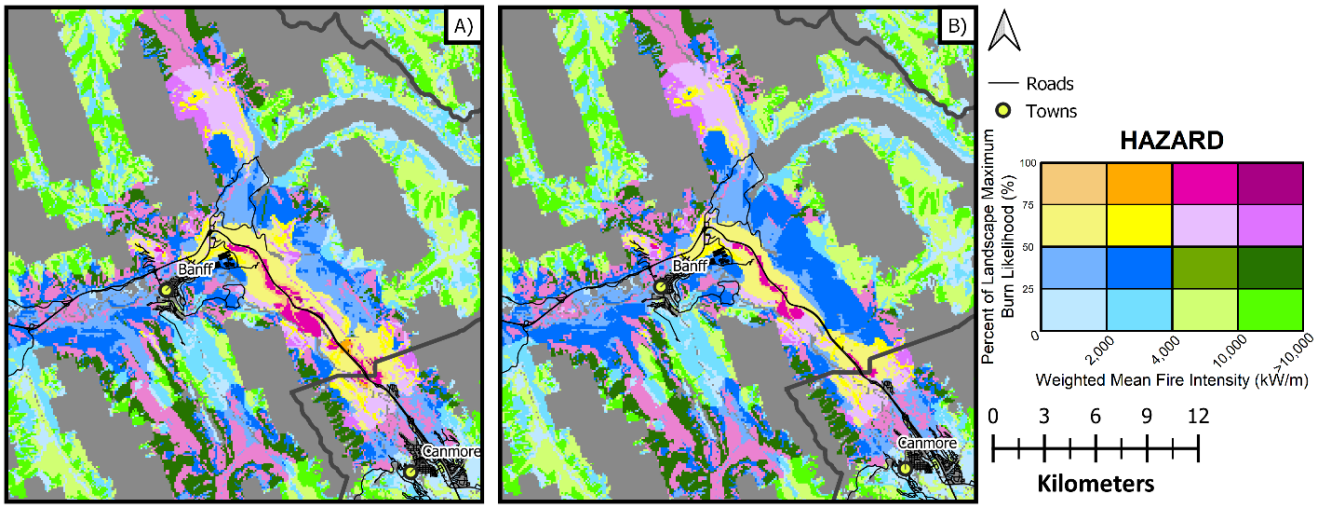

Figure 42. Spring (Apr. 1st – May 31st) hazard comparison of the fuels on the A) current landscape and B) no-fuels management landscape.

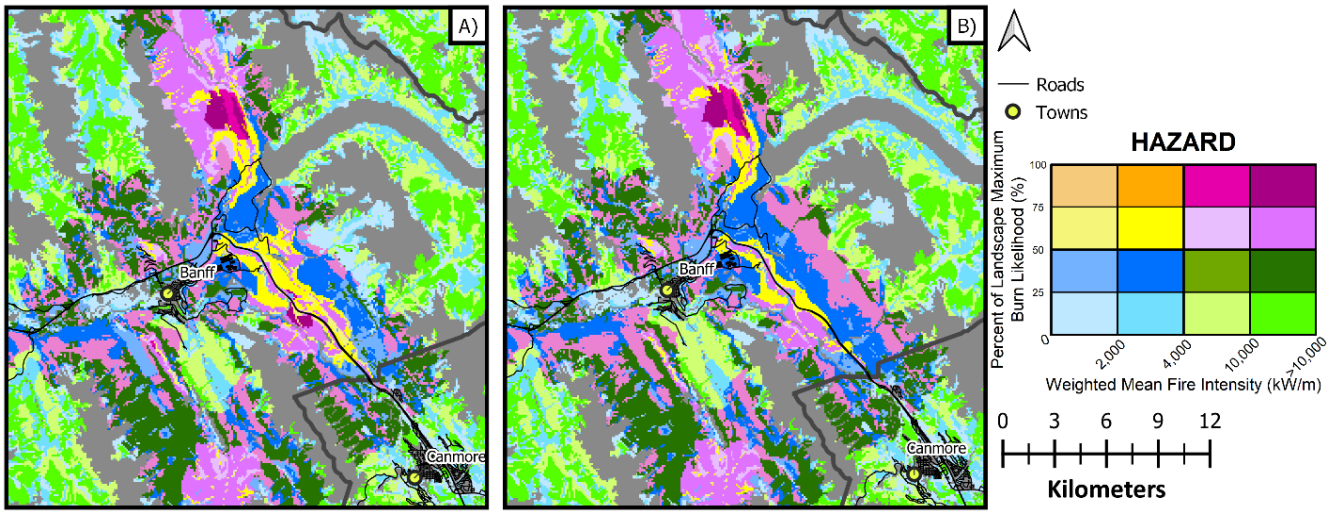

Figure 43. Summer (Jun. 1st – Sep. 30th) hazard comparison of the fuels on the A) current landscape and B) no-fuels management landscape.

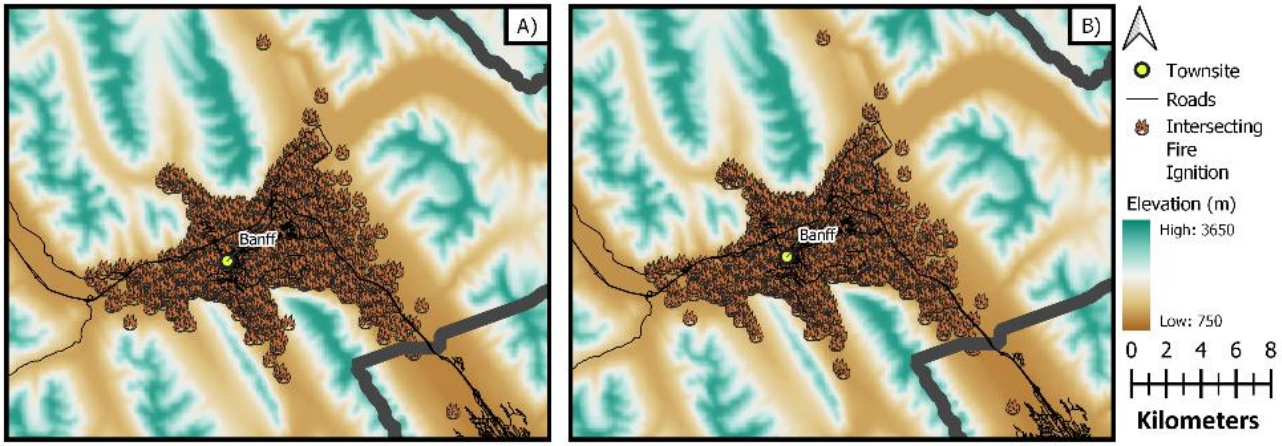

Figure 44. A) Spring (Apr. 1st – May 31st) and B) Summer (Jun. 1st – Sep. 30th) Banff townsite fireshed on the current landscape. Each point indicates a fire origin location that burned in to the Banff townsite.

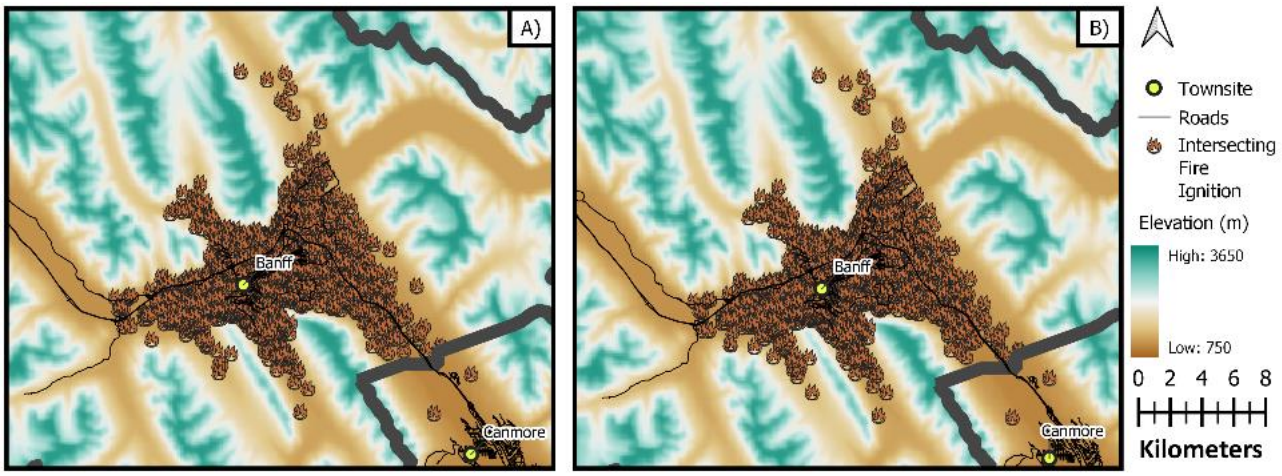

Figure 45. A) Spring (Apr. 1st – May 31st) and B) Summer (Jun. 1st – Sep. 30th) Banff townsite fireshed on the no-fuels management landscape. Each point indicates a fire origin location that burned in to the Banff townsite.

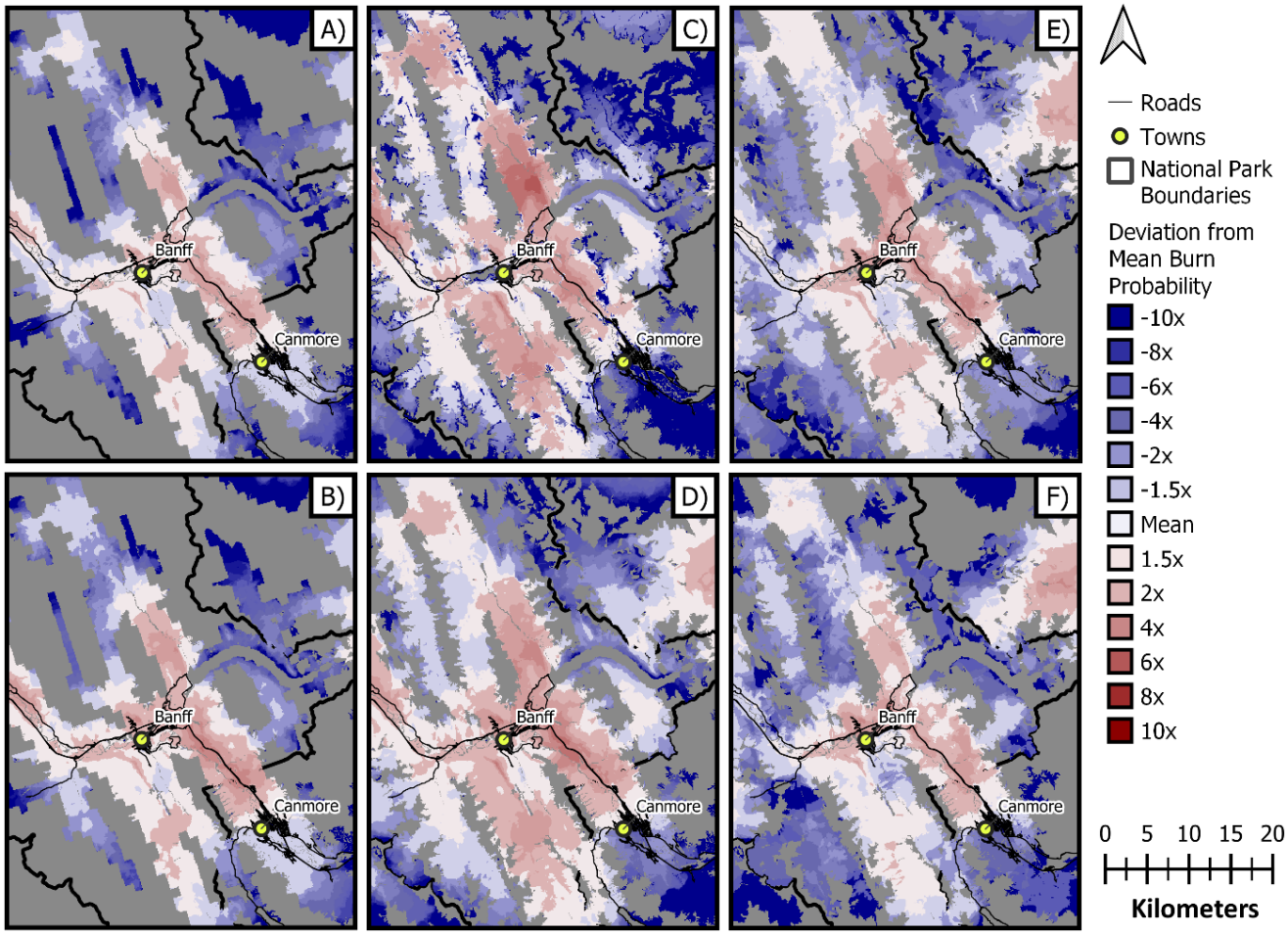

Figure 46. Burn probability for the townsite of Banff of the current landscape for A) early (Apr. 1st – Apr. 30th) and B) late (May 1st – May 31st) spring; C) early (Jun. 1st – Jul. 31st) and D) late (Aug. 1st – Aug. 31st) summer; E) early (Sep. 1st – Sep. 15th) and F) late (Sep. 16th – Sep. 30th) fall. Mean landscape averages for each season are 0.462%, 0.498%, 0.303%, 0.325%, 0.358%, and 0.464%, respectively.

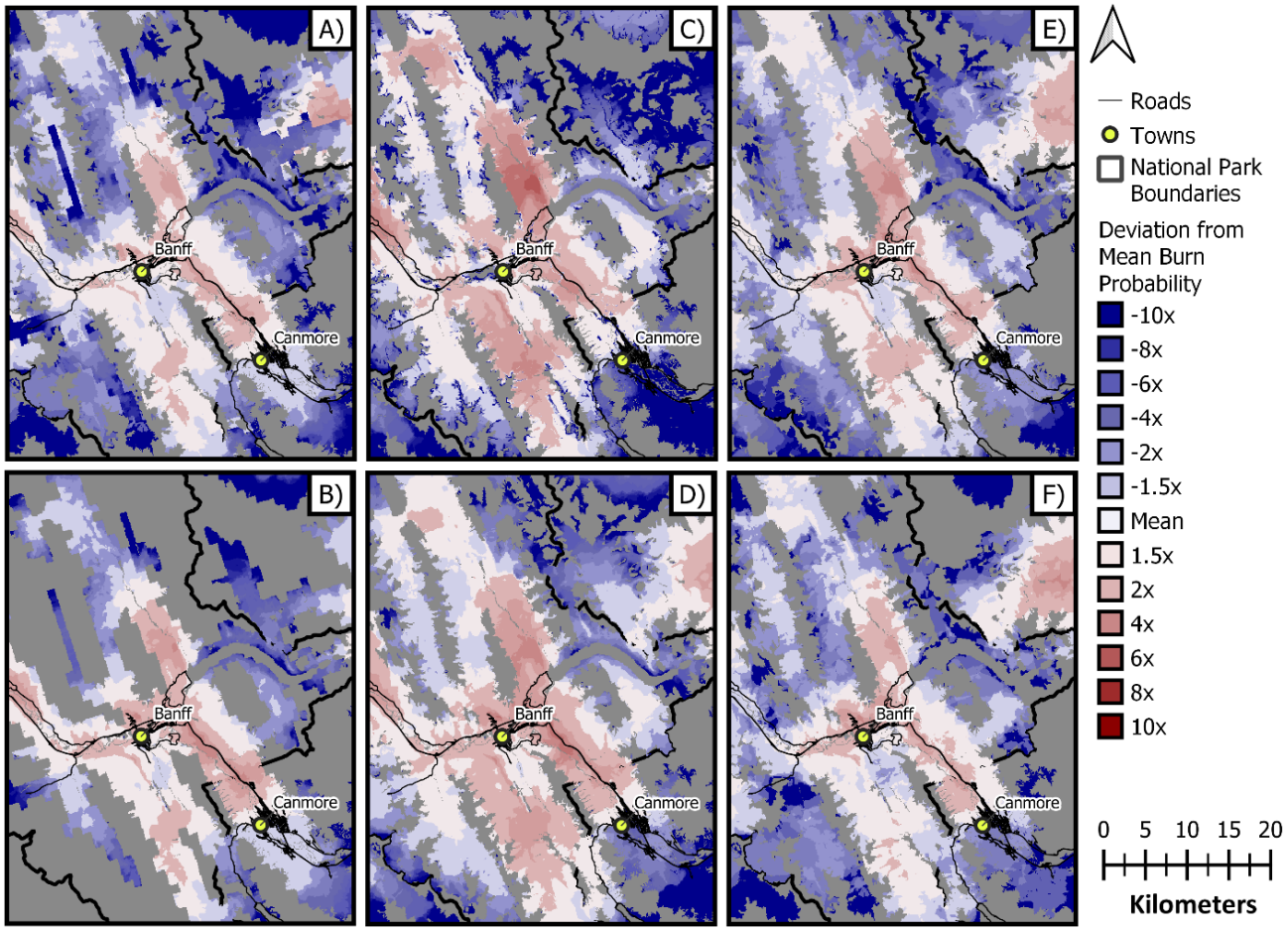

Figure 47. Burn probability for the townsite of Banff of the no-fuels management landscape for A) early (Apr. 1st – Apr. 30th) and B) late (May 1st – May 31st) spring; C) early (Jun. 1st – Jul. 31st) and D) late (Aug. 1st – Aug. 31st) summer; E) early (Sep. 1st – Sep. 15th) and F) late (Sep. 16th – Sep. 30th) fall. Mean landscape averages for each season are 0.460%, 0.494%, 0.308%, 0.319%, 0.346%, and 0.446%, respectively.

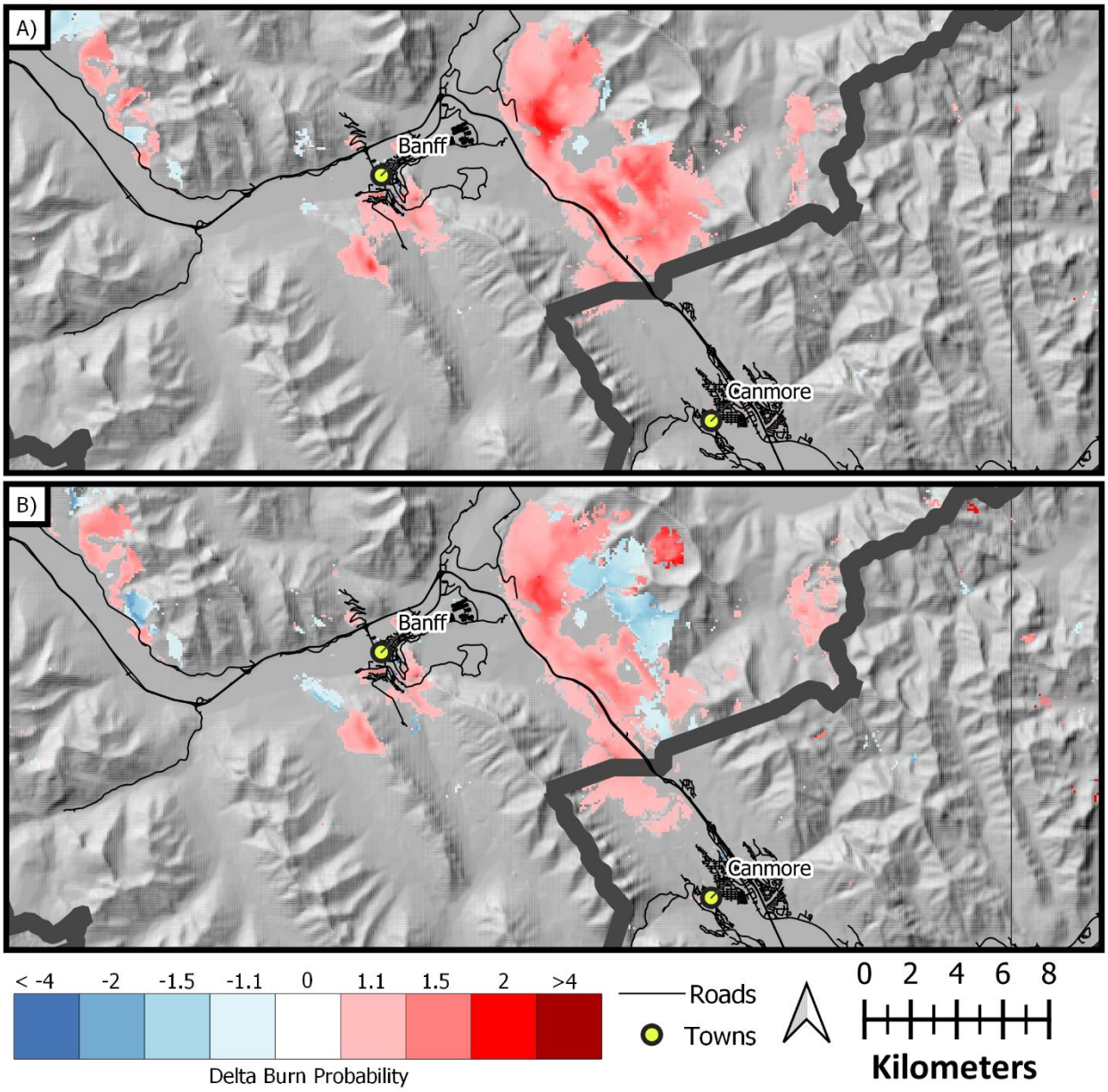

Figure 48. A) Spring (Apr. 1st – May 31st) and B) Summer (Jun. 1st – Sep. 30th) burn probability differences between the baseline current landscape and no-fuels management landscape. Blue colours show the decrease in burn probability while red areas show an increase in the burn probability due to the fuel treatments that have been applied.

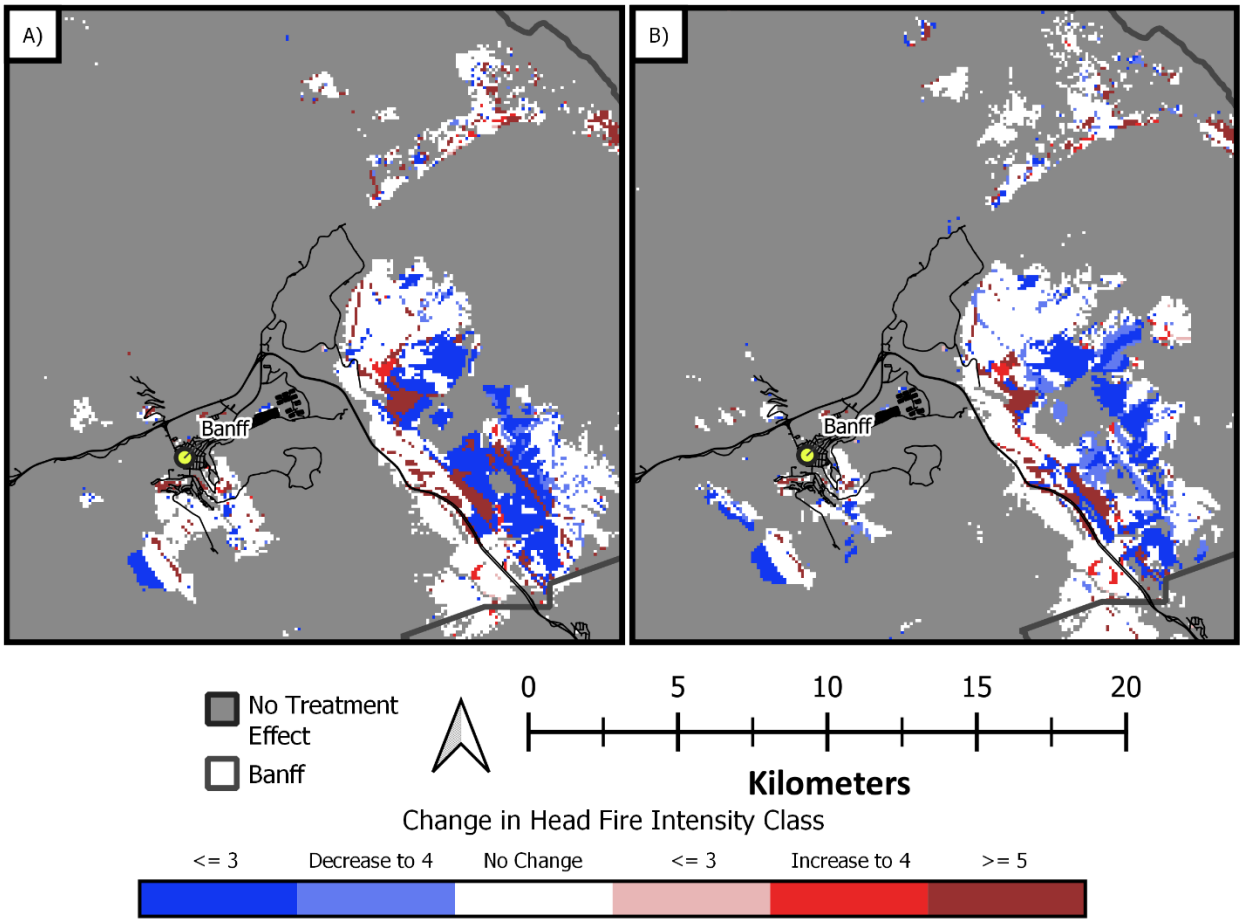

Figure 49. Change in Head Fire Intensity class from no-fuels management to current in A) Spring and B) Summer.

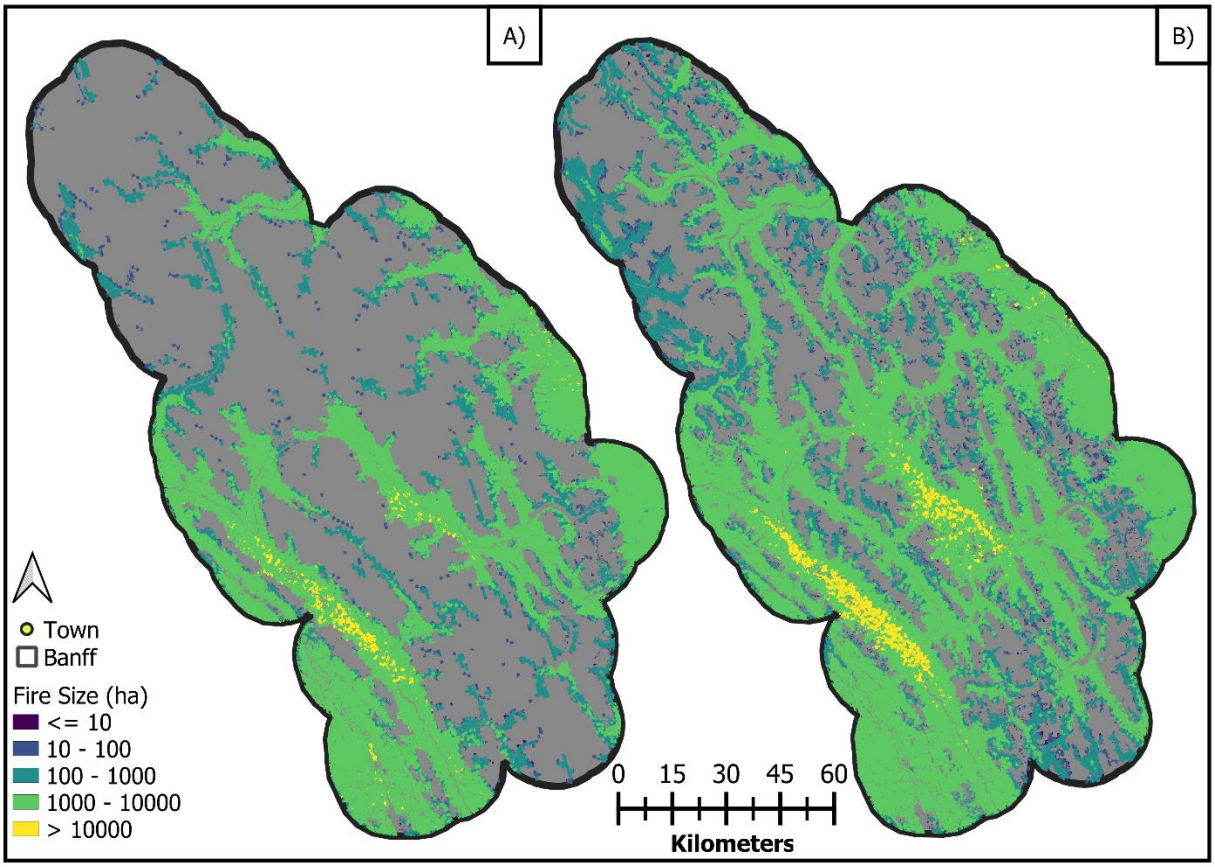

Figure 50. A) Spring, B) Summer source fire size under current fuel conditions. Source fire size indicates the mean size a fire igniting at a given location will potentially achieve, regardless of where it spreads to.

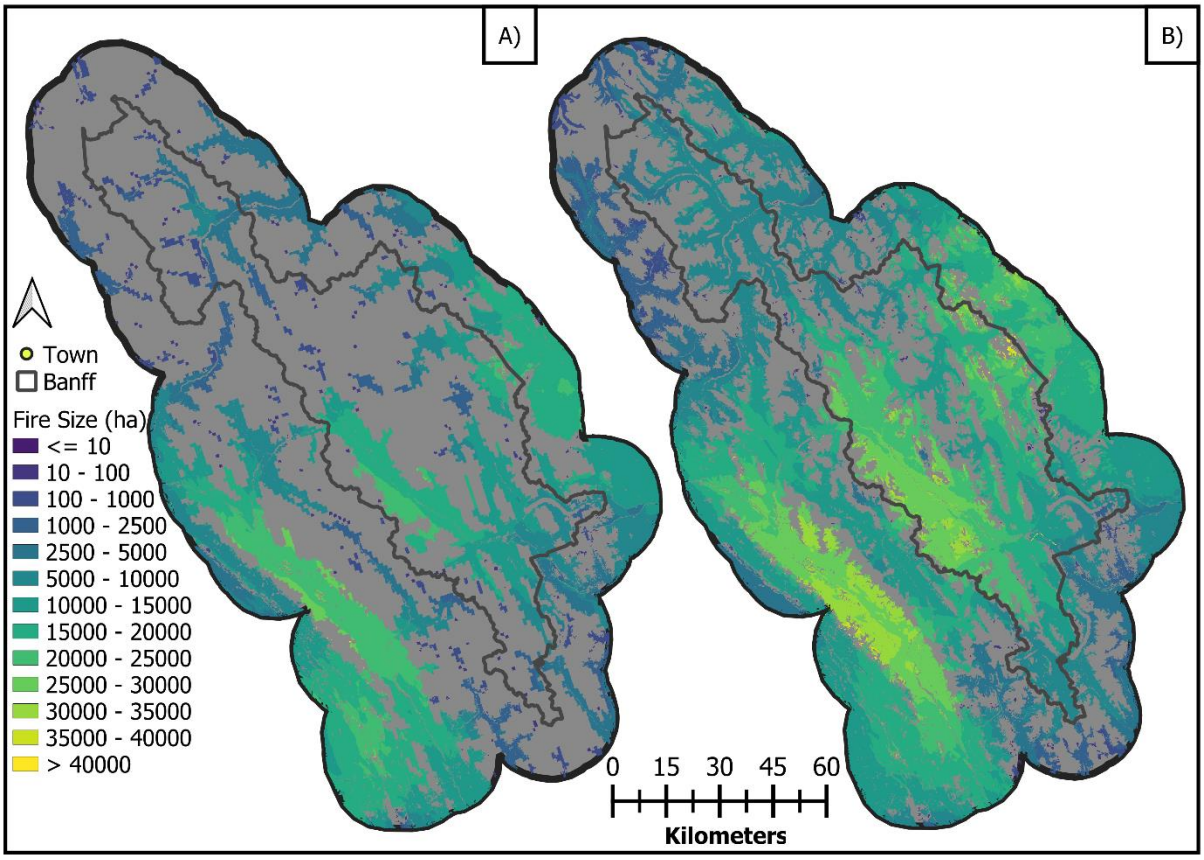

Figure 51. A) Spring, B) Summer sink fire size under current fuel conditions. Sink fire size indicates the mean fire size that burns a given location, regardless of its origin.

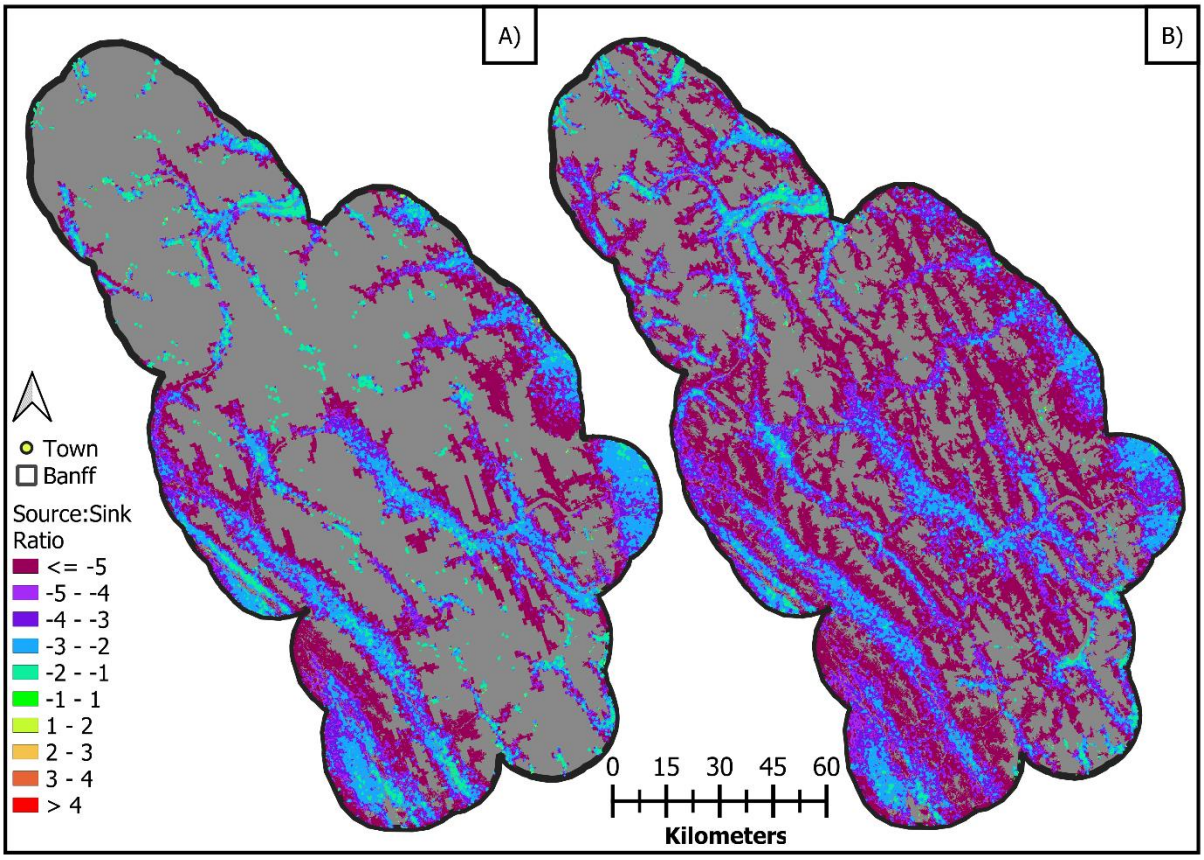

Figure 52. Source:sink ratio for A) Spring and B) Summer seasons under current fuel conditions.

Jasper National Park

When the Mountain Pine Beetle affected forests in Jasper National Park are classified as M3-65% Dead Fir, the town site fireshed is considerably larger in both spring and summer (Figure 53). The burn probability and intensity are highest in summer (mid-May to August inclusively, Figure 54). Burn Probability north of the town of Jasper is 10 times greater than the landscape average in Spring (Figure 55). There is high BP zone immediately to the east of the Jasper Park Lodge, however this is likely exaggerated somewhat due to our inability to model variability in density of MPB attack (this is described in greater detail in the discussion). The hazard (combined fire intensity and probability) indicates regions that show the highest BP are likely to burn at extremely high intensity (Figure 56), and these areas are those most heavily hit by the MPB (Figure 57).

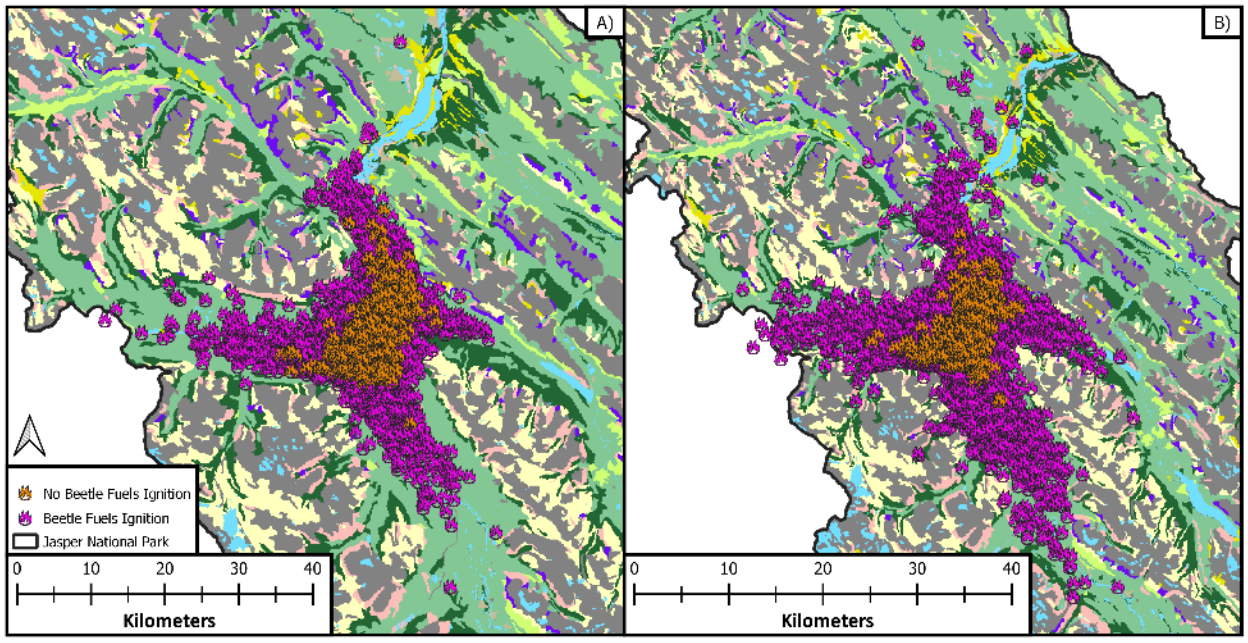

Figure 53. Simulated ignitions which burn into the Jasper town site for A) Spring and B) Summer. The different coloured ignitions indicate the size of the fireshed for pre-MPB infestation (orange) and post-MPB infestation (purple)

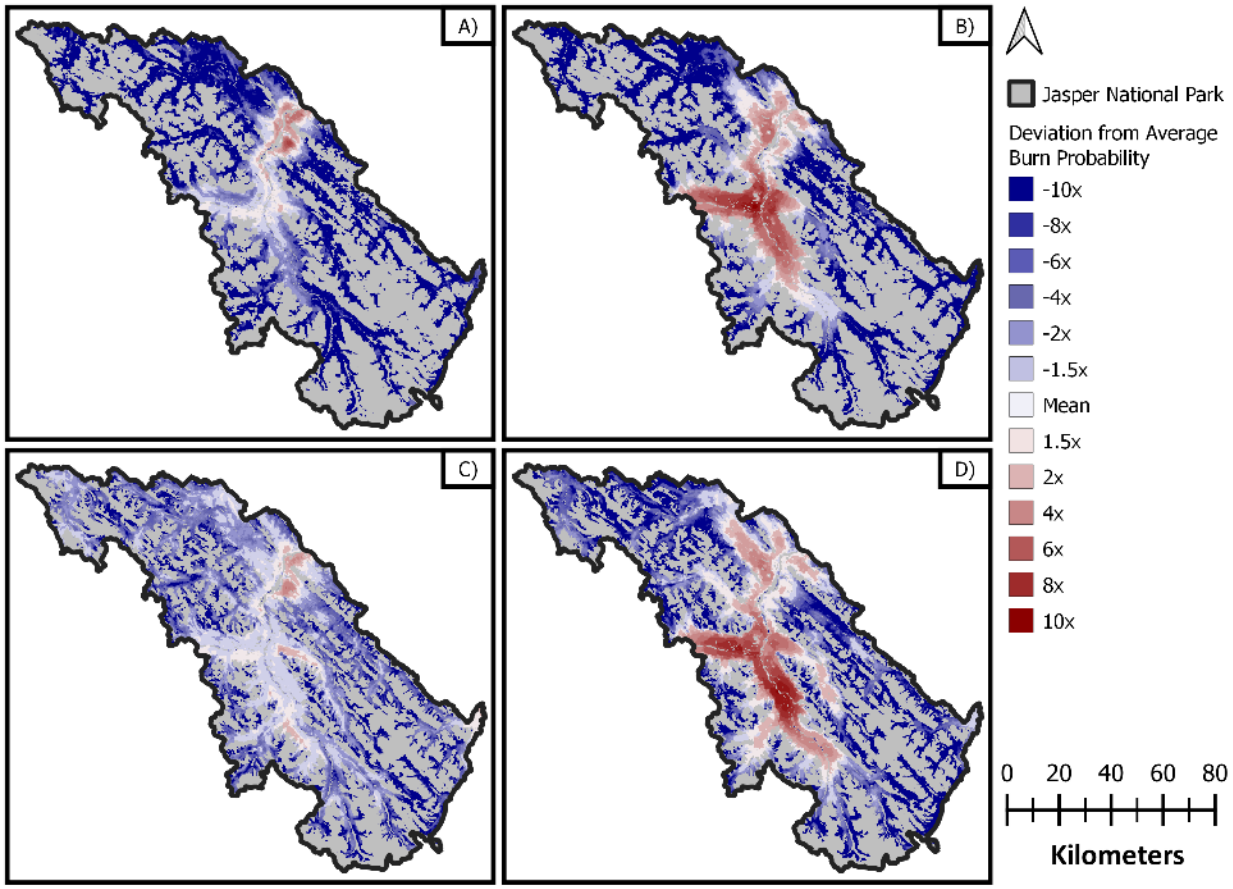

Figure 54. Burn probability for Jasper National Park in A) Spring and B) Summer pre-MPB infestation compared to post-MPB infestation (C) Spring and D) Summer)

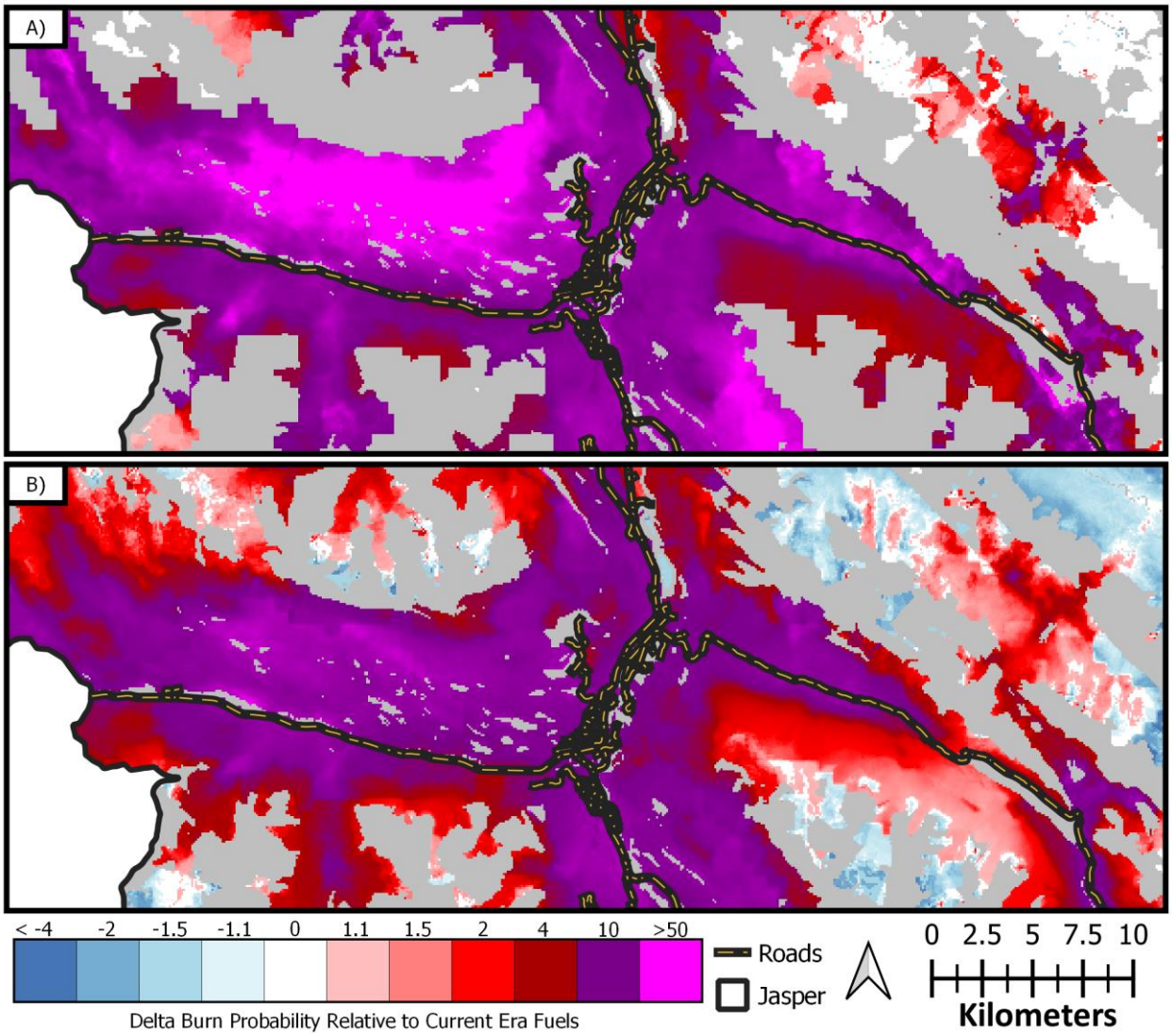

Figure 55. Difference in burn probability due to MPB-infestation (Comparing C3 vs M3-65% fuel types in areas attacked by MPB).

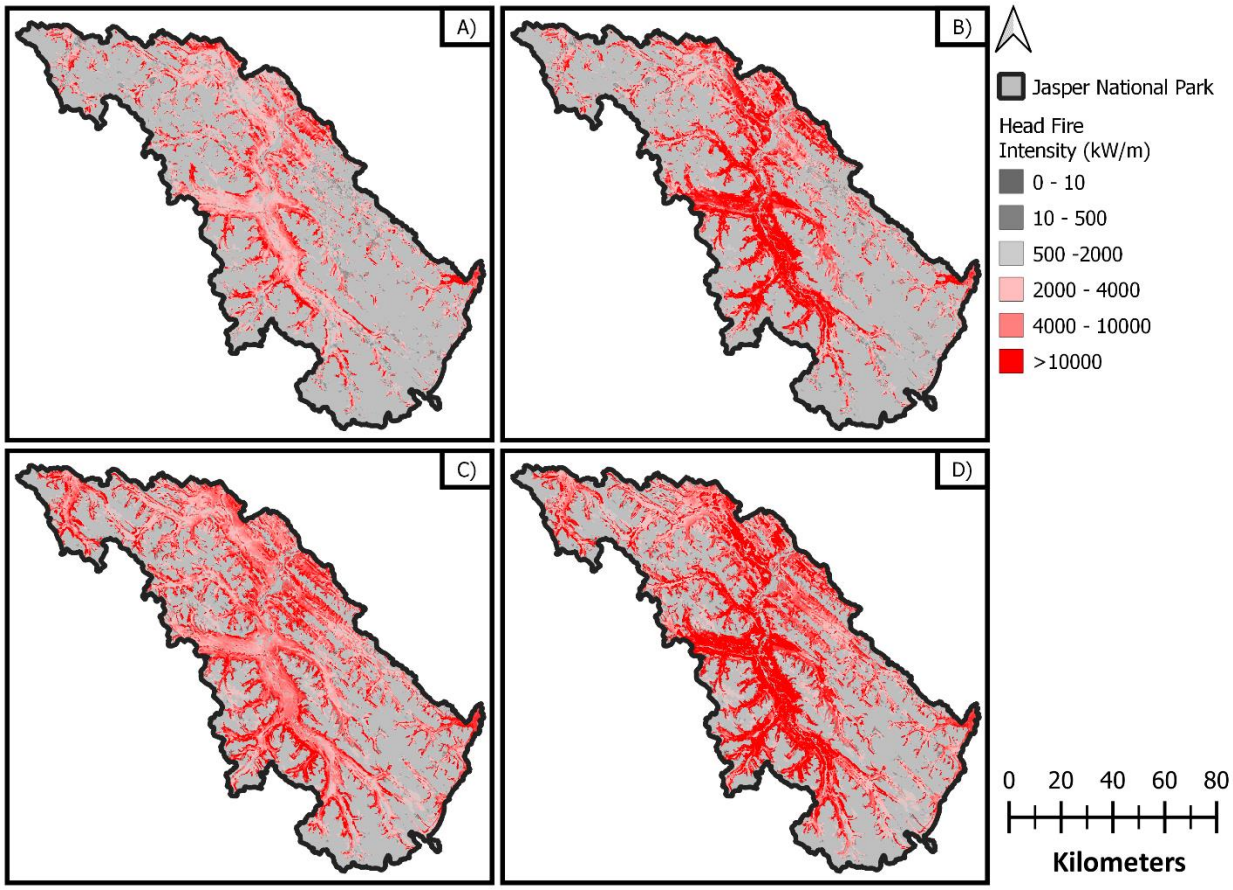

Figure 56. Head Fire Intensity class across the Jasper national park area for Spring and Summer in pre-MPB infestation ((A and B), and post-MPB infestation (C and D).

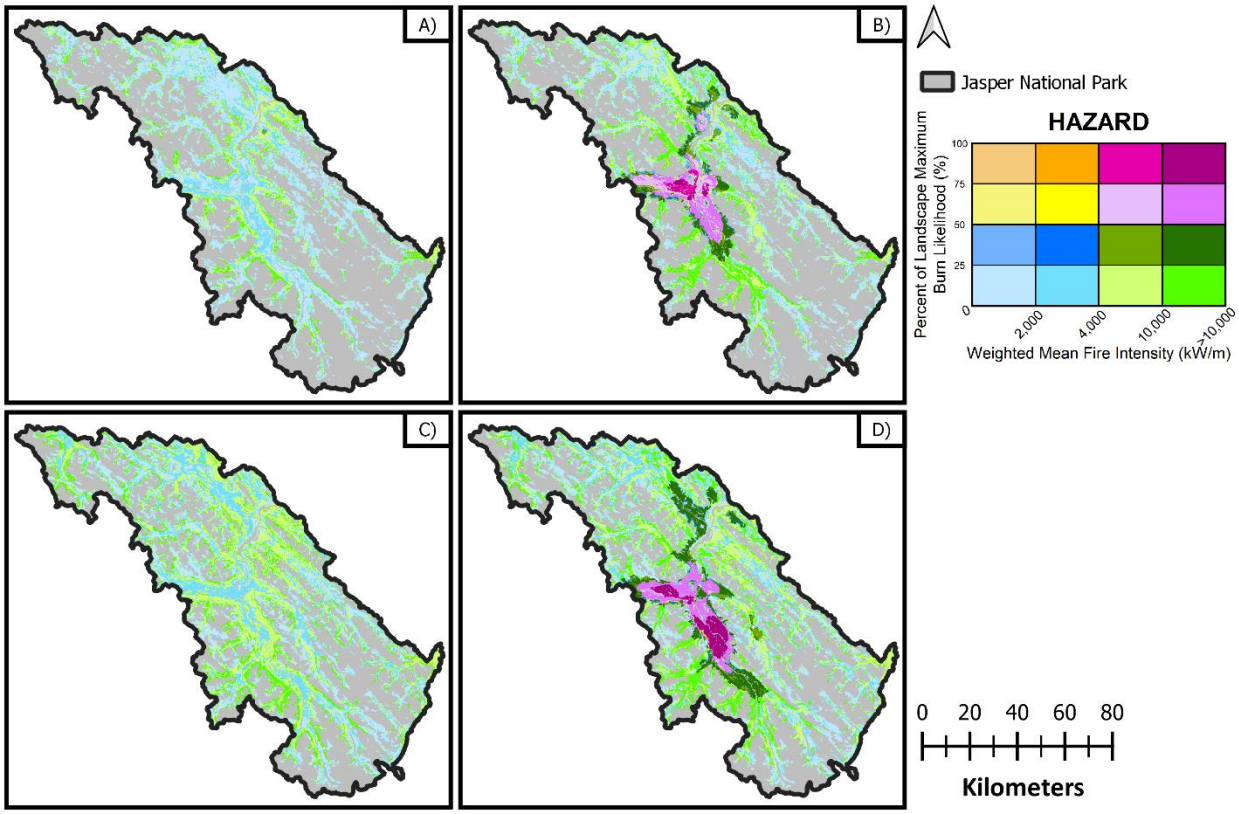

Figure 57. Wildfire hazard within Jasper National Park and around the Jasper townsite for A) Spring pre-MPB, B) Spring post-MPB, C) Summer pre-MPB and d) Summer post-MPB

Waterton Lakes National Park

Prior to the Kenow wildfire (September 2017), the region of the park with the highest burn probability was in the Belly River and Crooked Creek watershed region of the eastern side of the park, where the BP is more than 4x the landscape average BP, however the South Kootenay and Akamina passes leading from British Columbia through the park also showed high BP (Figure 58). Potential fire intensity is very high (Intensity Class V or VI) in the coniferous fuels, but low (IC II or III) in the montane and grassland portions of the park. The fireshed for the town of Waterton is mostly confined to the Blakiston Creek, Akamina Parkway, and along the western shore of Waterton Lake, however it is possible for fires burning higher up the Bauerman Creek drainage to reach the townsite. The latter is largely due to fires that burn up through the Crandell gap. However, the 2017 Kenow wildfire completely changed the landscape, and much of the park currently has very low to no BP (Figure 59), but there are important caveats associated with this that will be described in more detail in the discussion. Furthermore, the fireshed for the town of Waterton has largely been shrunk to the townsite itself due to the entire surrounding landscape being recently burned. The hazard (both pre- and post-Kenow) is highest in the Belly River region of the park (Figure 60 and Figure 61). While the mean BP of the pre-Kenow fire landscape suggests that the region of the park that burned was in a moderate to low BP area, Figure 62 shows that in late summer the Akamina and Blakiston valleys had very high BP, and this is where the Kenow fire burned. Seasonal BP was reduced under the footprint of Kenow, as expected due to a drastic change in fuel availability (Figure 63).

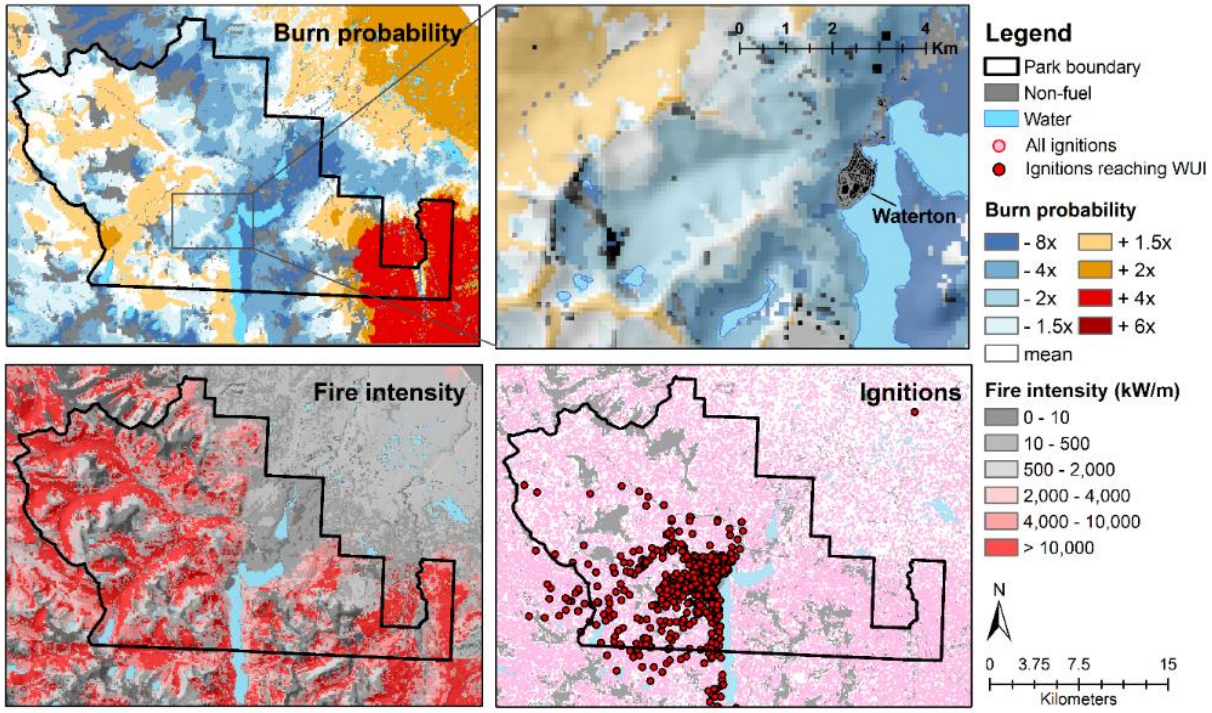

Figure 58. Pre-Kenow (2017) wildfire landscape and around the townsite of Waterton, AB, Canada, showing Burn Probability, Fire Intensity, and the Waterton townsite fireshed within Waterton-Lakes National Park. Burn probability is classified as the deviation from the mean landscape burn probability.

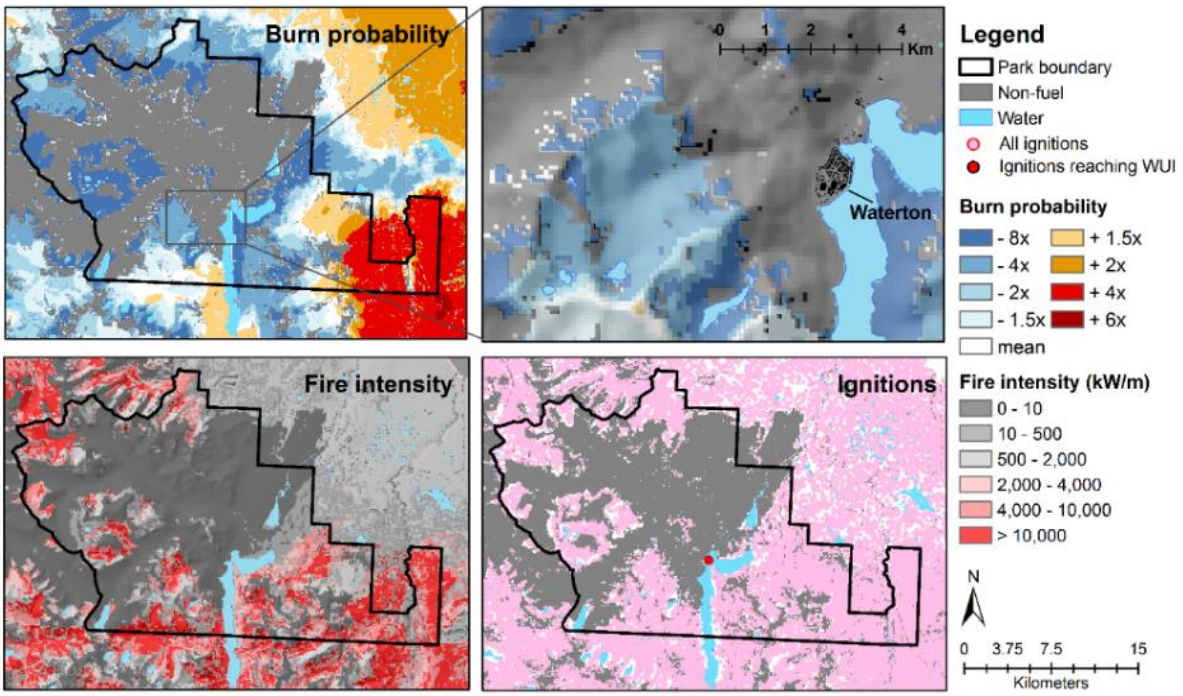

Figure 59. Post-Kenow (2017) landscape and around the townsite of Waterton, AB, Canada, showing Burn Probability, Fire Intensity, and the Waterton townsite fireshed within Waterton-Lakes National Park. Burn probability is classified as the deviation from the mean landscape burn probability.

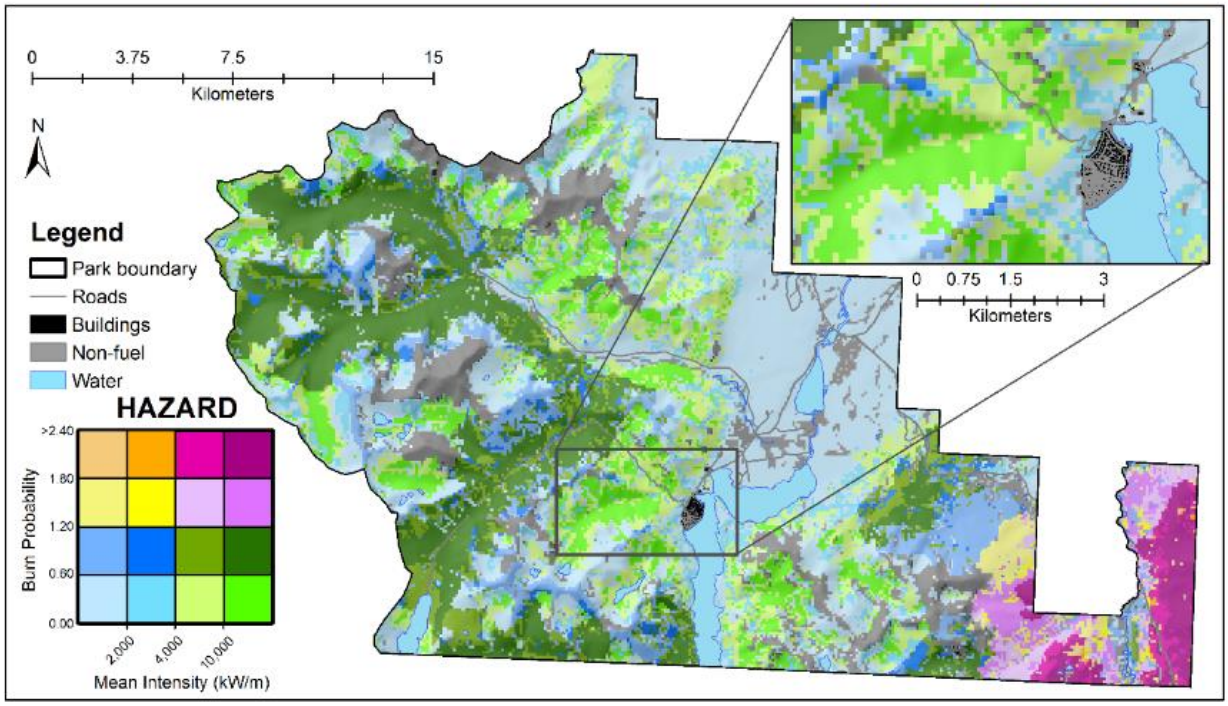

Figure 60. Wildfire hazard within Waterton-Lakes National Park and around the Waterton townsite (inset) pre-Kenow (2017) wildfire. Hazard is classified as the product of the burn probability (%) classed in equal intervals (<0.60, 1.20, 1.80, > 2.40) and the fire intensity (kW/m) classification (<2,000, 4,000, > 10,000).

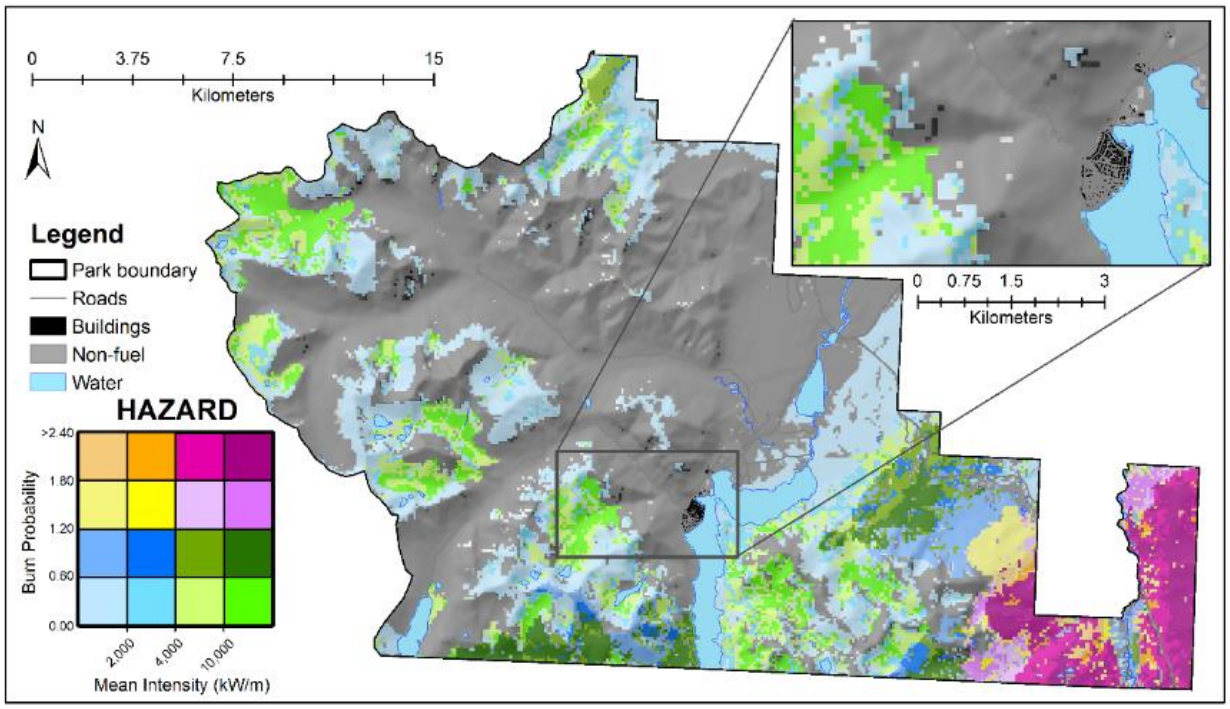

Figure 61. Wildfire hazard within Waterton-Lakes National Park and around the Waterton townsite (inset) post-Kenow (2017) wildfire. Hazard is classified as the product of the burn probability (%) classed in equal intervals (<0.60, 1.20, 1.80, > 2.40) and the fire intensity (kW/m) classification (<2,000, 4,000, > 10,000).

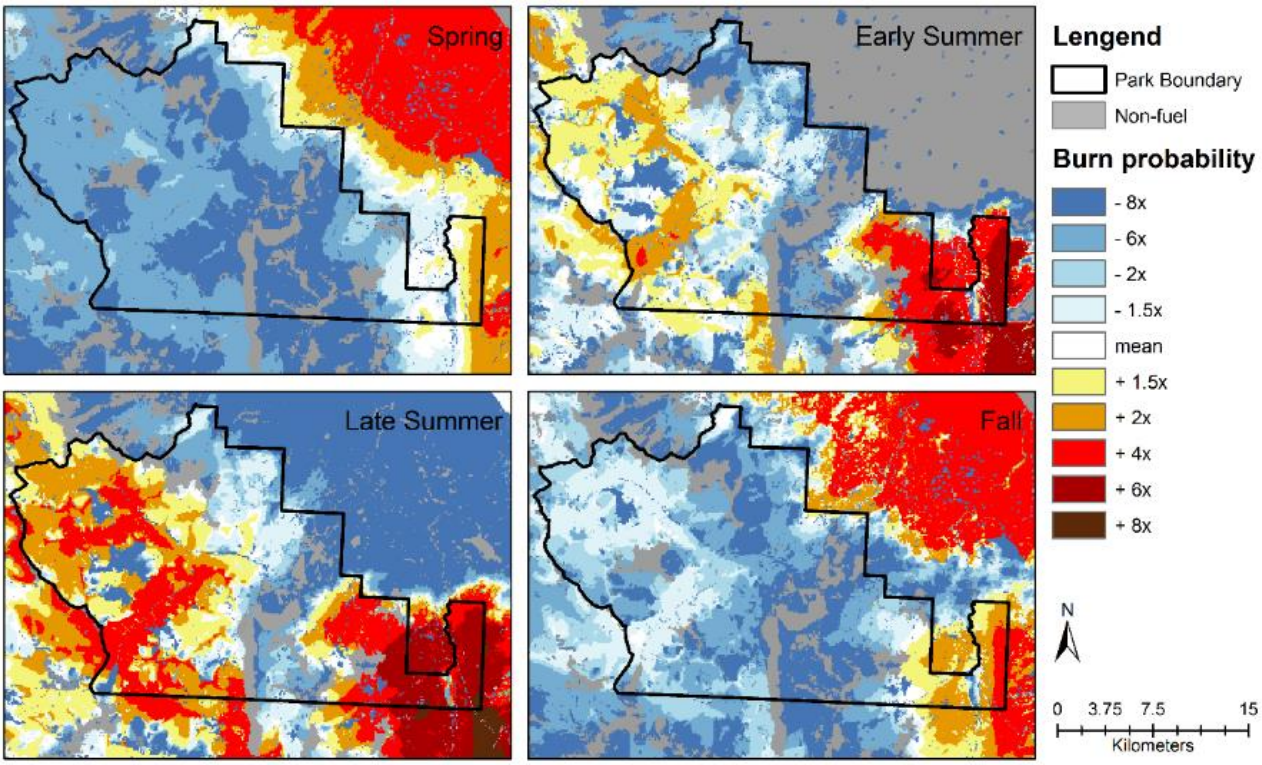

Figure 62. Modelled burn probability for Waterton-Lakes National Park pre-Kenow (2017) wildfire fuels landscape presented as the difference from the calculated landscape mean (0.625%) subdivided by seasonality including Spring (Apr. 1st – May 15th), Early Summer (May 16th – Jul. 15th), Late Summer (Jul. 16th – Aug. 30th), and Fall (Sep. 1st – Sep. 30th). Mean landscape averages for each season are 0.8657%, 0.5163%, 0.4359%, and 0.9447%, respectively.

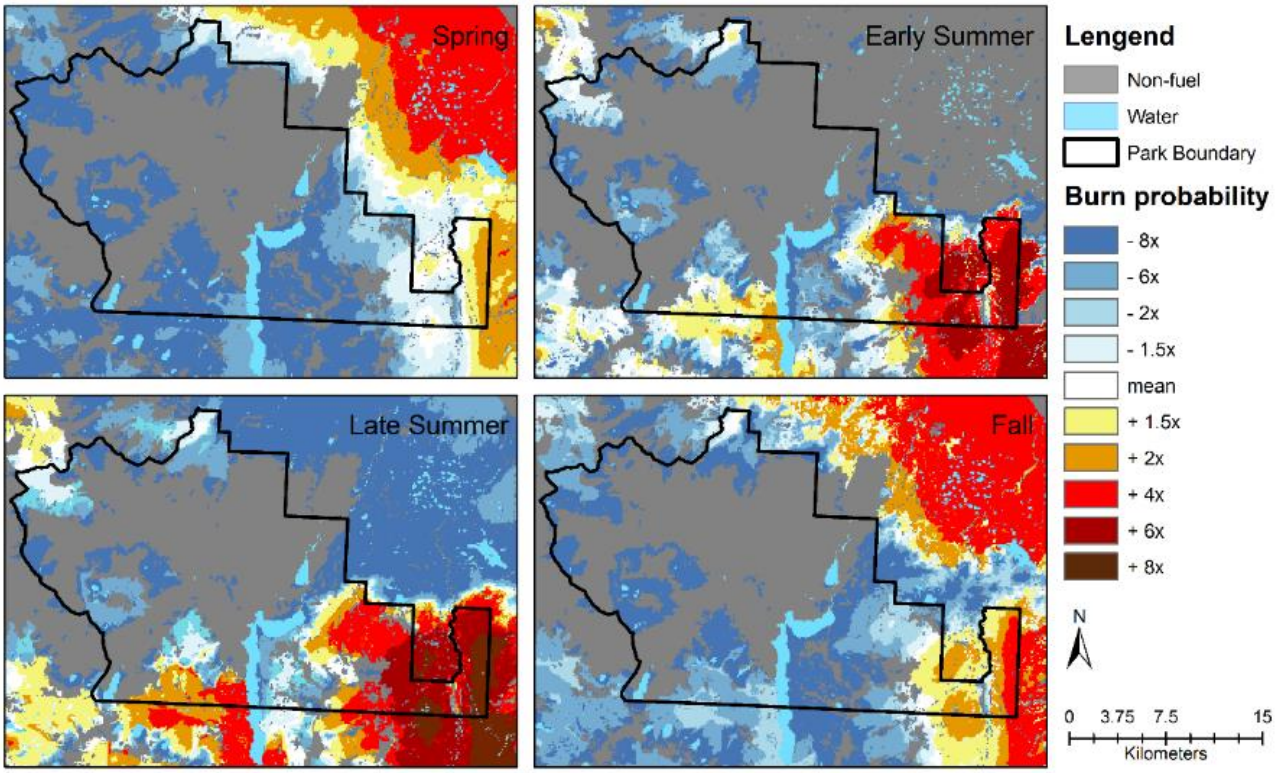

Figure 63. Modelled burn probability for Waterton-Lakes National Park post-Kenow (2017) wildfire fuels landscape presented as the difference from the calculated landscape mean (0.725%) subdivided by seasonality including Spring (Apr. 1st – May 15th), Early Summer (May 16th – Jul. 15th), Late Summer (Jul. 16th – Aug. 30th), and Fall (Sep. 1st – Sep. 30th). Mean landscape averages for each season are 1.0833%, 0.6166%, 0.4589%, and 1.1709%, respectively.

Riding Mountain National Park

The greatest risk of fire within the park is surrounding the townsite of Wasagaming, along the east and south shores of Clear Lake, where the BP is up to 4x the landscape average. Other than within the park, the greatest risk on the landscape of wildfire probability is to the northwest corner outside of the park (Figure 64) in the agricultural land. In spring and fall when the crop stubble is cured the wildfire risk on the proximity of the Park is greatest (Figure 65). In summer, the greatest burn probability is within the National Park, where fire intensity is greatest in coniferous dominated fuel types.

Wildfires that burn into Wasagaming all originate within the proximity of the townsite and within Park and more south within the agricultural lands outside of the National Park, and as such the greatest risk to the townsite are those ignitions which can possibly start east within the park and south within the agriculture land. The area surrounding the town of Wasagaming is of low probability of wildfires however the intensity of a potential event is great (Figure 66). Spring and fall pose considerable risk to the park as there is a large landscape with cured crop stubble, which can burn very easily and spread rapidly. Within the park the area of greatest hazard is due to a moderate burn probability but the highest of the fire intensity classes.

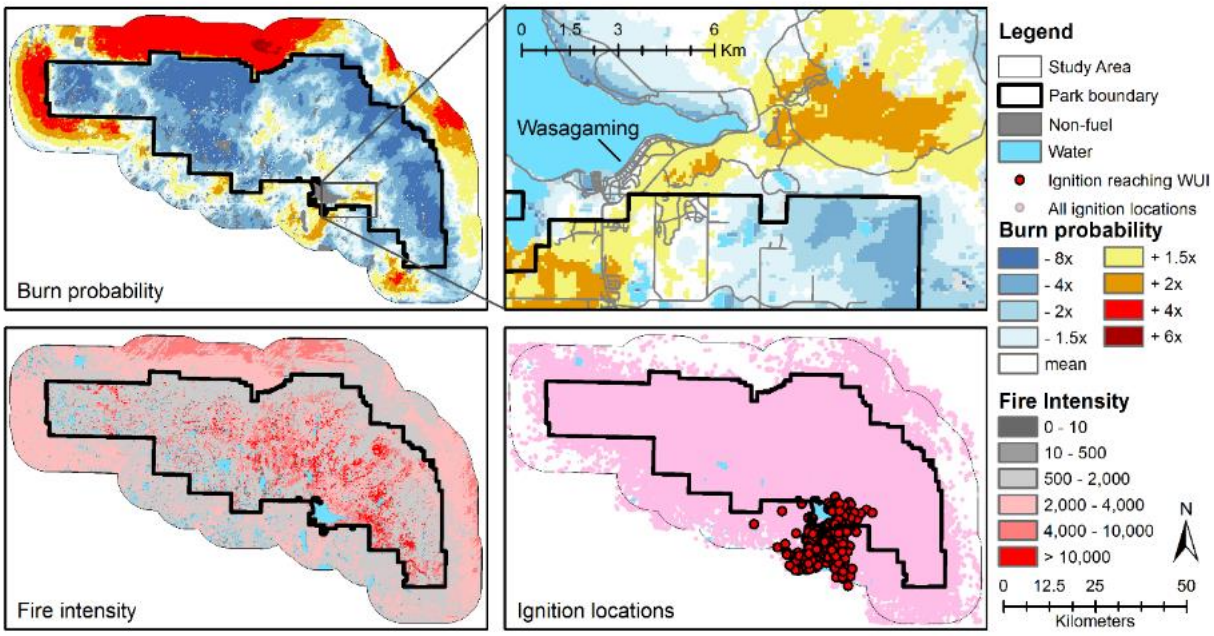

Figure 64.Composite of Burn-P3 simulated wildfire burn probability on the landscape and around the townsite of Wasagaming in Riding Mountain National Park, MN, Canada, the fire intensity, and all Burn-P3 ignition points during the simulation model (n=100,000). Burn probability is classified as a function of deviation from the mean (0.1989%) of the burned landscape, where +4x would be four times the mean landscape average and the maximum (0.8757%) simulated for the Landscape. Wildfire intensity are classified as per the Field Guide to the Canadian Forest Fire Behaviour Prediction (FBP) System. Fire intensity classes are divided from 1 to 6, divided as follows <10 kW/m, 10 - 500 kW/m, 500 - 2,000 kW/m, 2,000 - 4,000 kW/m, 4,000 - 10,000 kW/m, > 10,000 kW/m. Ignitions were classified as those reaching the WUI (wildland urban interface) aka Wasagaming town site (red) and those that do not grow a fire reaching the WUI (pink).

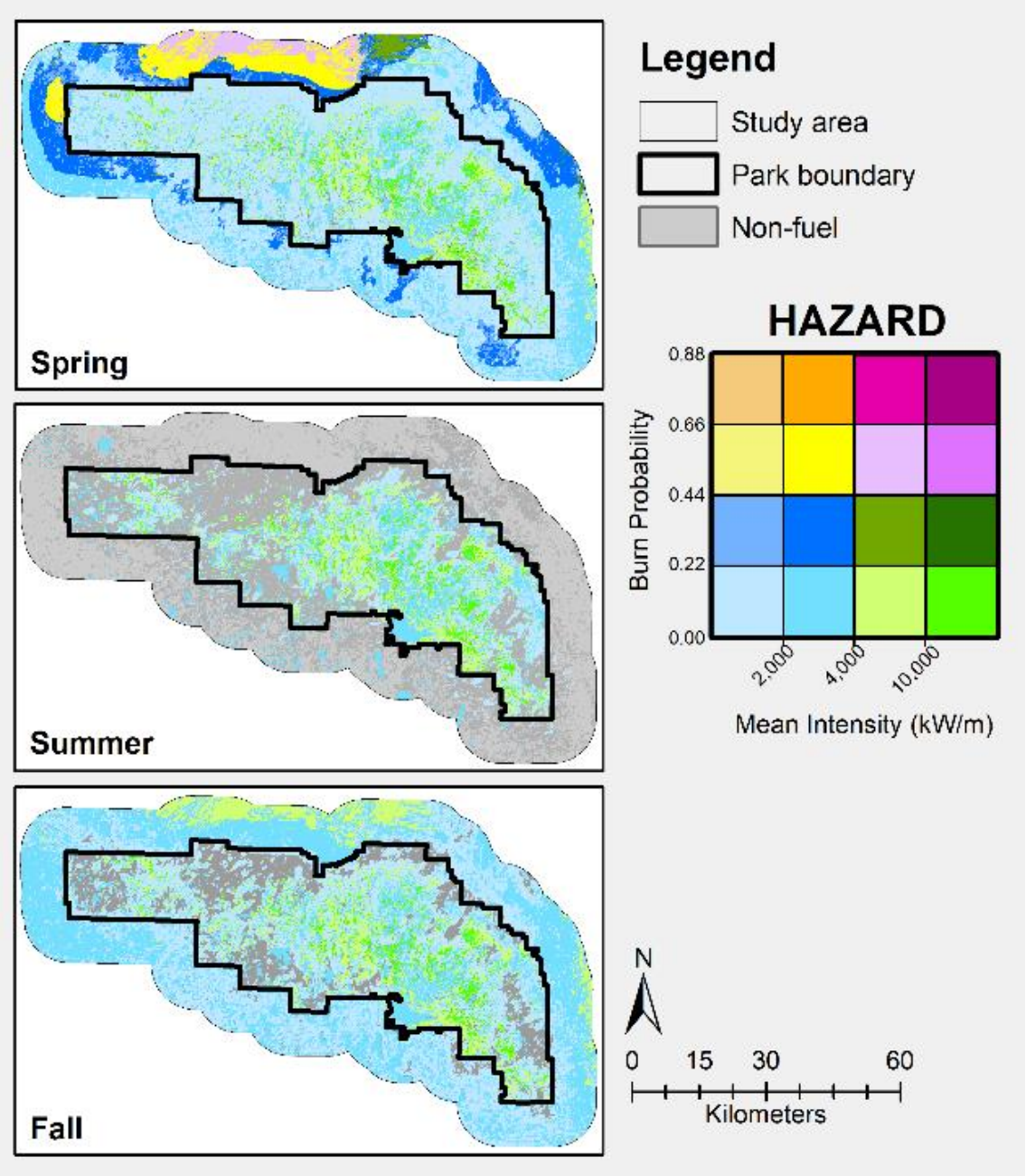

Figure 65. Wildfire hazard within Riding Mountain National Parks and 10km buffer as classified by the burn probability (%) and average fire intensity (kW/m) for the entirety of the simulation (Apr. 1st to Sep. 30th).

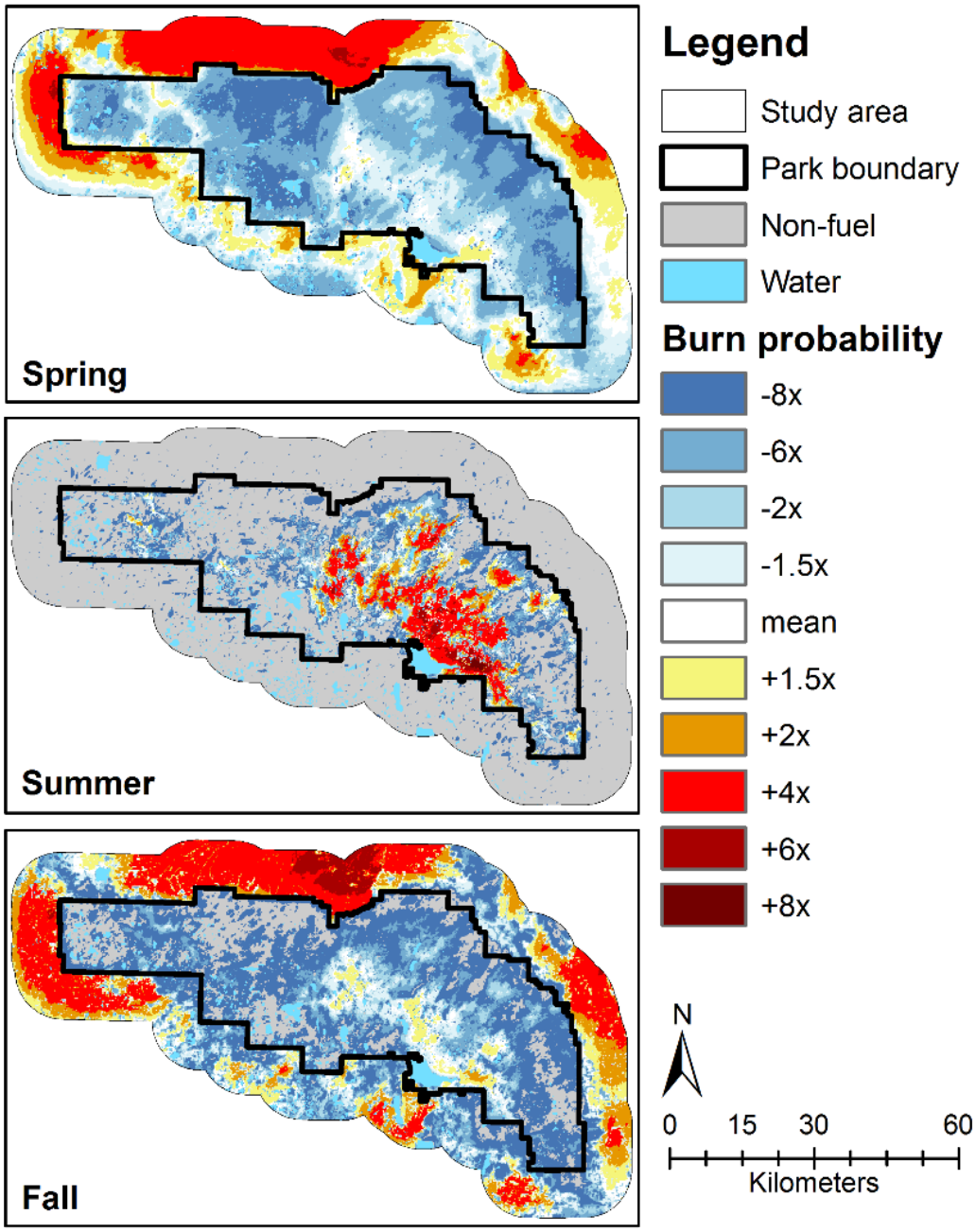

Figure 66. Modelled burn probability for Riding Mountain National Park presented subdivided by seasonality including Spring (Apr. 1st – May 16th), Summer (May 15th – Aug. 15th) and Fall (Aug. 16th – Sep. 30th). Mean landscape averages for each season are 0.2018%, 0.1483%, and 0.2506%, respectively.

Discussion

General Discussion

This study A) identified the current burn probability (BP) and hazard throughout the Rocky Mountain Parks and Riding Mountain landscapes and to the town sites within them; B) examined the BP and hazard facing Banff town site in greater detail; C) modeled the effect that the fuel treatments surrounding the town of Banff have on BP and hazard; and D) examined the elevated risk in Jasper posed by recent Mountain Pine Beetle killed forests. Across all modeling domains we found strong seasonal effects on BP and hazard, as well as significant impacts from recent wildfires within some of the modeling areas. Furthermore, fuel treatments close to the town of Banff have helped to reduce the burn likelihood in the town site itself, however further work is required to quantify this effect in a more robust fashion, as the FBP system itself is not sensitive enough to be able to model unique fuels that result from physical fuel treatments. Fuel treatment effects will be discussed in more detail in the BYK Specific Discussion section.

In our assessment of the current burn probability and wildfire hazard, we found that there was a strong effect of season on the resulting patterns of the landscape. This held true across all the modeling domains in this study. While we refer to the “seasonal” effect in many places in this report, note that “season” does not explicitly mean calendar dates, rather: “Spring” refers to the period after most snow has melted, but aspen trees have not yet leafed-out, and the grass is still in a cured and matted state; “Summer” indicates the period where aspen trees are green, and grass is too green to carry fire; and “Fall” indicates the period where grass is cured (and flammable), but aspen trees still have leaves. By the time true autumn arrives in the mountains when the leaves have fallen, the day length is so short that fire is a very rare event, and thus we have not modeled this condition. In some modeling domains we also included sub-seasons such as dividing “spring” into periods with fully cured to partly green grass or declaring different parts of summer to account for grass being green at the start, but partially cured and burnable in the later period.

These distinctions in seasonal fuel conditions can be explained by the Fire Behaviour Prediction (FBP) system of the Canadian Forest Fire Danger Rating System (CFFDRS) (Forestry Canada Fire Danger Working Group, 1992) which states that when grass curing levels are higher

than 50%, grasses cannot carry fire, and thus when curing is higher than that value, grasses act as a barrier to fire spread. In the early spring, late summer, and fall, however, grasses contribute to elevated rates of spread, BP, and hazard. Furthermore, in spring, cured grass is "matted" and classified as fuel type O1-a because of the overwinter snowpack weight on top of the grass, as opposed to summer or fall cured grass, which is standing (fuel type O1-b, Forestry Canada Fire Danger Working Group, 1992). The rate of spread is higher in O1-b, but intensity is higher in O1-a. Similarly, leafless aspen is burnable, whereas leaf-on aspen is very difficult to burn. As such, areas with aspen and grass on the landscape show considerable variability in BP and hazard due to seasonal differences. Open canopy woodlands with significant grass cover in the understory should exhibit lower BP and hazard in the late spring and early summer due to the grasses being green and non-flammable, however this is not always captured in modeling studies such as this, as the FBP Fuel type C7 (which is most often used to describe this vegetation type) does not have a green-up trigger to slow fire spread in the summer.

Another primary driver of seasonal differences in the patterns of BP and hazard is weather. Even in areas with fuel types such as closed canopy coniferous fuel types like C2, C3, and C4, we see different BP and hazard because of the weather conditions in the different seasons. Cooler spring temperatures with higher relative humidity lower the Fire Weather Index (FWI) values, which in turn decrease the Rate of Spread (ROS) and Head Fire Intensity (HFI). The seasonal BP and hazard maps should provide some guidance in terms of identifying the parts of the landscape that are most prone to fire due to the different influences of seasonal weather patterns and phenological changes in fuel conditions.

Displaying wildfire risk by different seasons is a new approach for using the Burn-P3 model. In the past, the primary output of the Burn-P3 model for any given region was to produce a singular "burn probability" map (Parisien et al. 2005, Parisien et al. 2013, Stockdale et al. 2019a, Stockdale et al. 2019c, Beverly et al. 2009, Beverly and McLoughlin 2019, Wang et al. 2016). While these whole-of-fire-season BP maps are mathematically accurate, they hide the seasonal differences which are critical to understanding, managing, and mitigating wildfire risk on the landscape. These hidden details can lead to significant misrepresentation of wildland fire risk, where the overall likelihood in a given area may seem low, but the likelihood of fire in a specific

season may be very high. This seasonal high may be masked by a lower overall number of fires that occur in that season. This primarily occurs with spring fires being largely masked by a shorter season, creating fewer fires that don't contribute much to annualized BP maps. However, flammable grasses and aspen stands in the spring can lead to rapid spread events that grow to massive fires, such as observed in the 2011 Slave Lake wildfire, and the 2016 Fort McMurray wildfire. By separately displaying seasonal BP, Intensity, and Hazard maps, fire managers can have a more accurate picture of the fire danger present on the landscape at different times of year. Even if the overall likelihood of an event is low, it is vital to understand its potential for occurrence relative to other locations on the landscape at the same time as the consequences and impact of such fires can be very high. Individual simulated fires don't burn across all seasons, they burn within a specific season with distinct fuel and weather characteristics; in essence, in many places spring and summer fires are burning on different landscapes.

Recent wildfires in Waterton Lakes National Park (WLNP) and Kootenay National Park (KNP) have created temporary conditions whereby burn probability and hazard will be lower for several years, but as vegetation regrows within these recent burns, the fire danger will begin to rise again and change the overall landscape patterns. As such, it is important to monitor vegetation succession within the boundaries of the Kenow Fire (2017, WLNP) and the KNP fire complexes from 2018 (much of which had also burned within the past 15 years). Within the Kenow fire itself, there are parts of the landscape (low elevation, and microtopographic low points) that have had significant herbaceous vegetation regrowth. This herbaceous vegetation can contribute significantly to fall fire hazard when it is cured, or in the spring after snowmelt, and prior to green-up of new vegetation. However, there are also many places within the Kenow Fire boundaries that burned to mineral soil, and these areas will be slow to redevelop flammable vegetation (Lentile et al 2007). A return to flammable conditions is not wholly negative as wildfire is a natural and desirable process in these landscapes.

Over time, new wildfire disturbances are also inevitable, and these will alter the BP and hazard of the landscape. In some cases, these new wildfires may provide positive benefits to reducing wildfire risk to numerous values on the landscape, and the fires themselves contribute

towards restoring the appropriate fire regime for the parks in general. When major changes in fuel conditions due to wildfire occur, or as vegetation recovers on old burns so that it can carry fire again, it will be important to re-do the Burn-P3 simulations. For this reason alone, we highly recommend that all Burn-P3 model users save their "Ignition List" outputs when running their initial simulations. This allows a new fuel grid (i.e. post-wildfire or fuel treatments) to be used for a new simulation that can then be run with minimal investment of start-up time. By using the "Replay" function of the Burn-P3 model whenever major changes occur in the fuel grid, managers can always have the most accurate picture of wildfire risk on their landscape. There is no specific length of time that the current BP forecasts are limited to, but studies have shown the reburn potential of sites can be reduced for several years, depending upon the location and severity of the previous fire (Héon et al. 2014; Parks et al. 2016; Beverly 2017).

The observed effect of recent fires limiting future fire likelihood is a solid rationale for establishing fuel treatments and prescribed fires in key locations. There are several ways to "manufacture" barriers to reduce fire risk, such as modifying vegetation (which changes the fuel type through either silvicultural intervention or prescribed fires) to affecting ignition likelihood on the landscape (Agee et al. 2000). Placement of the fuel treatments is an important consideration as their effectiveness is spatially limited in terms of how far they are placed from the value of interest to be protected (Stockdale et al. 2019c). The relatively localized effect of treatments suggests it is a good idea to have numerous treatment zones to cover off fire threats coming from different directions and under different conditions. In the mountains, with prevailing winds driving fires primarily in the direction of valley orientation (Rogeau et al. 2016), the best place to establish fuel treatments is in locations that break up fuel continuity along the valleys. This sheltering effect of fuel treatments is temporary, however, because as vegetation regrows on the site, and as standing dead timber from prescribed burns falls to contribute to the surface fuel loading of a site, the reburn potential rises and returns to the pre-disturbance BP within a few years. Therefore, it is important to have redundancy, flexibility, and continued maintenance and revisitation of these fuel treatments to recognize the temporally limited nature of the protection afforded by them and extend their usefulness. A current study led by Dr. Denys Yemshanov, with Drs. Parisien and Stockdale's participation will be investigating new

methods in spatial optimization to determine where to place fuel treatments and prescribed fire.

Our analysis of the firesheds surrounding the various town sites revealed that highly damaging fires can originate in many locations on the landscape if the conditions are severe. No modeling study can examine all possible combinations of fire start locations with all possible weather conditions, and so it is vital to note that fires can burn into these town sites that start in locations not indicated by these fireshed analyses, however, the nature of Monte Carlo simulations does indeed show that this is unlikely (but not impossible). Some of the potential fires that may burn into communities appear to come from large fires igniting at considerable distance from the community, but these larger “danger” fires tend to burn under conditions that require several days of significant fire spread with shifting wind patterns; this too is not an impossibility but are unlikely events. Another element to be aware of with Burn-P3 modeling is that it does not take suppression capabilities into account, and therefore while firesheds indicate the greatest risk to the town sites of Banff, Field, Waterton, Jasper, Wasagaming and Lake Louise are all posed by simulated fires starting closest to the towns themselves, these fires also would likely be actioned very quickly and have a lower likelihood of growing to become problematic in the first place.

However, in extreme weather conditions, even nearby ignitions can be problematic, because fires that are closer to the value at risk can reach that location in a short period of time. This was the case in Fort McMurray, where the fire ignited close to town, but due to weather and fuel conditions, this fire grew very rapidly and overwhelmed suppression capabilities within minutes. In these extreme cases, fires can burn massive areas of the landscape, and will burn through virtually all vegetation types. We should not only be concerned with fires that ignite close to values at risk, but as large fires also burning several spread-days away from town sites can potentially posing a danger to the communities within the National Parks. The White Rock Lake Fire (2021) which burned through Monte Lake and threatened Vernon, BC exhibited rapid fire growth that was uncontrollable by the time initial attack resources showed up within 30 minutes of ignition. Heightened awareness of the whole fire environment (detailed fuels and weather forecasts) is critical both during fire events, and

during periods of high fire weather danger. No model outputs should ever override decision making during such emergency situations. The pre-Kenow fireshed for Waterton town site showed that fires starting outside the Park in BC were unlikely to reach the town site, but it did indeed happen. Because “unlikely” events are possible in extreme cases, it is crucial to have evacuation plans in place, and decision-making processes that can be implemented quickly. When the Kenow Fire threatened the community in September of 2017 Parks Canada staff acted early to call an evacuation. If they had waited until the fire had been inside the Park itself, the evacuation would have been too late as anomalous conditions occurred with the Kenow fire burning through the night and the spread rate of the fire was such that people could have been entrapped in the town site and other areas of the park. As the Kenow fire demonstrated in Waterton, mountain fires can burn very intensely and move down-valley very quickly. Redundancy in fuel treatments scattered across a broad landscape is the only true insurance against losses to wildfire coupled with well-developed evacuation plans.

Banff, Yoho, and Kootenay Specific Discussion

The areas of the BYK landscape with the highest BP are in Rocky Mountain Trench to the west, the Kootenay Valley, the northern end of the Bow Valley, and in the Ghost-Waiparous region to the east. The areas of highest BP are similar between both spring and summer, however, while the southern Bow Valley is of lower BP than the north in the spring, the south end increases in in BP substantially in the summer, thus making the whole of the Bow Valley at substantial risk. The hazard in the region surrounding Banff town site is considerably higher in summer than it is in the spring, however in both seasons the potential fire intensity is quite high. In all regions of the BYK landscape, the potential fire intensity is very high, which definitely poses challenges to fire suppression activity. Most of the variability in BP, intensity, and hazard stem from ignition likelihood; these regions have the highest human use, and are therefore at the highest probability of fires starting there. During the course of this modeling exercise a substantial wildfire burned during September of 2020 (the Devil’s Head Fire). This fire burned during what was modeled as “early fall”, and the actual fire perimeter was contained within one of the highest BP zones in this modeling exercise. While this is only a single fire, and cannot

be used in and of itself to validate our model predictions, it does lend some support to the overall conclusions of this study.

We found that the fuel treatments in the immediate vicinity of the town of Banff have only marginally reduced the BP, and in some areas surrounding town they appear to have increased the BP, but we also found a larger reduction in fire intensity in the immediate surroundings of the town, and these results must be looked at together. The changes resulting in increased BP are merely an artefact of how the Burn-P3 model is structured: fires burn for a set period of time, and so when a fuel type with a higher rate of spread (O1) is substituted for one with a lower rate of spread (C3), the fire will grow larger in the same amount of time. At the same time, though, this fuel type change will result in a large decrease in fire intensity. The small change in BP due to fuel treatments shown by this modeling can be misinterpreted to mean that they are ineffective, however, because the results still assume free-burning fires, and do not account for the fact that many of the fires that would theoretically burn through these treatments would be more easily suppressed, the BP would be further reduced because of increasing suppression likelihood. Our results showed a decrease in intensity within the fuel treatments, and in much of the area show “no change” in intensity, but again this is likely due to the insensitivity of the FBP system to subtle changes in stand structure that do not result in full-scale reassignment to a new fuel type. However, this modeling exercise has only begun to explore their effectiveness, and more results will be coming in the next phase of this research (as of November 2021, this work is in progress). The conversion in area that would have burned at Intensity Classes V and VI (and been uncontrollable) to Intensity Class III or IV (which are much more controllable) is vital to increasing the likelihood of suppression effectiveness. Fuel treatments such as these were the very reason the town site of Waterton was saved during the Kenow fire, as the fuel treatment zone on the edge of town reduced fire intensity to a level that permitted fire fighters to hold their ground there and initiate suppression actions that would otherwise have been impossible (Scott Murphy, *personal communication*).

Further complicating the testing of fuel treatment effectiveness are limitations of the FBP system used for fire growth projections in Canada. Many of the areas that have had prescribed burns are classified as slash type fuels due to the presence of lots of large downed wood. While

the slash fuel designation provides a decent fuel type for the purpose of determining Rate of Spread (which is the determinant of final fire size in Burn-P3), it almost certainly overestimates the intensity of the modeled fires. This overestimate of intensity results in an inflated hazard, when in reality, many of these fires would be much easier to suppress than if they were burning in “true” slash, which includes large volumes of small debris wood, which dries very quickly and inflates the Initial Spread Index considerably.

The source-sink dynamics of the region show some interesting patterns, however, it is important to remember that these dynamics are restricted to the range of conditions that were modeled in this exercise: namely fires burning with weather conditions conducive to active crown fire spread in the C3 fuel type. Source dynamics describe the mean fire size that would be expected to grow if ignited at a particular location, and the largest fires in the summer in the BYK landscape originate throughout the central Bow Valley, Kootenay Valley, and the western foothills around the Panther and Red Deer River valleys. In the spring, large fires are possible in the Bow and Kootenay valleys, but their potential is significantly smaller than it is in the summertime. The smallest fire sources are the numerous high elevation valleys branching off from the larger main valleys, and this is as expected as the fires have less room to grow, and winds have to be aligned perfectly in order to drive fire downslope and out of these locations. Sink dynamics refer to the mean fire size that burns a given location, and again we find the largest sinks in much of the same region we see large sources. The common location for both maximum sinks and sources is explained by these valleys being very broad, having continuous coniferous forest cover, and prevailing wind direction tends to take these fires along the major axis of these valleys. As Rogeau et al. (2016) found, smaller isolated valleys tend to burn the least frequently, and with smaller overall fire sizes when they do, lending support to the idea that these locations act as fire refugia. The ratio of source:sink tells an interesting story too, in that most of the landscape is a large source for fire, meaning most locations are likelier to burn from fires of 2-4 times the size of the fires that they generate.

Jasper Specific Discussion

The results presented in this study of the BP and hazard in JNP are preliminary at this time. Due to a lack of data upon which to make more sophisticated fuel type calls we made simplistic assumptions about the impacts of mountain pine beetle (MPB) on the fuel type and treated all MPB-affected stands the same way (calling it all M3-65%). We know that the area of extremely high BP and hazard to the east of the townsite/ north end of the Skyline trail is almost certainly an overestimate of the actual conditions, however we do not have data to support changing model inputs. Parks managers informed us that the MPB attack through this area was much spottier than it was elsewhere in the Park, which likely means that our declaration of an M3-65% fuel type is causing fire conditions in the model to be too extreme in these locations. One major challenge associated with this modeling is that the severity of MPB attack is recorded in classes, and the highest class is anything greater than 30% of the stand being "red". There is undoubtedly a major difference in wildfire rate of spread and intensity in a stand with 30% red trees than in one with 90% red trees, but we do not have the data to be able to make this sort of distinction.

If we assume the Mountain Pine Beetle in Jasper National Park has had no impact and leave the "affected stands" as their current fuels, C-3, considerably lower burn probability and intensity are seen. This was expected and provides a good baseline for expectations of increased fire behaviour. It is important to note that setting all C-3 to M3-65% is the most pessimistic scenario and likely real-world events would demonstrate a blend of the two scenarios we are presenting here.

Waterton Lakes Specific Discussion

This project began before the Kenow fire occurred, which is why we have presented pre- and post-Kenow fire BP results and fireshed analyses. Clearly, a fire of this magnitude has caused long term change in the park. The areas that show no likelihood of burning because of the Kenow fire will not remain as such indefinitely. As of the late summer of 2019, we have already observed substantial vegetation growth along Blakiston Creek downstream from Red Rock Canyon. Much of this new vegetation growth is herbaceous vegetation, so the BP is very

low while this is green, but when cured in the spring and fall, the risk of fire is substantial. Fires occurring in this area and fuel type also pose significant danger to regenerating conifer seedlings and could push the area into long period of non-forest condition.

The Belly River region of the park is the area with the current highest BP and hazard and is of considerable concern to the managers of the park. The likelihood of ignition is relatively low in this region of the park as there are very few areas where people can be, apart from the highway and Belly River Campground. The campground itself, however, is along the river, with considerable deciduous vegetation surrounding it, and therefore at the time of peak occupancy by campers (summer), the risk of fire escaping from here is quite low. However, the impact side of the fire risk equation is where the concerns are highest. If a fire were to occur in this region of the park, there are very few anchor points from which suppression operations could begin, and a fire could spread out into the grasslands outside the park. If this occurred when fuels were cured (grasses with >50% curing), and with the winds that can occur in this region, fires could carry for a considerable distance across the landscape outside of the park.

Riding Mountain Specific Discussion

Most of the fire risk to the town site of Wasagaming is in the forests to the immediate south and east of the town site. Clear Lake serves as significant shield to the town, protecting it from potential fires that might approach from the north or west. While the fireshed for Wasagaming is constrained to the very-near landscape of the town itself, it is important to note that the lake is not so large as to prevent ember showers if winds were very strong or a large convection driven fire were to occur across the lake. The Burn-P3 modeling platform does not account for ember transport causing spot fires ahead of a main head-fire, and fire managers need to be aware to communicate this risk effectively to the public at large.

As the seasonal BP and hazard maps reveal, the surrounding agricultural landscape interacts dynamically with the Park itself. In spring, the hazard and fire likelihood are highest outside the park, and this is the result of crop stubble in the fields. In the summer, the situation is reversed with the highest hazard in the Park itself, and the agricultural landscape largely being unburnable. In the fall, the situation returns to what it was like in the spring, again due to

stubble on the agricultural fields. This is also one of the largest sources of error in these model runs, as it is difficult to assess the likelihood of ignition in the agricultural landscape. Based on discussions with Parks staff, we have assumed that the practice of stubble burning is common in this region, which is why we see such an elevated BP and hazard in the spring/fall. It is important to note that while this elevates the risk considerably, the likelihood of suppressing fires in the agricultural landscape is also quite high due to the fuel load being quite low and the number of linear fuel breaks from which suppression operations can be conducted is very high. The presence of these linear features is in and of itself an issue with this modeling as the roads themselves are too narrow to appear as "nonfuel" in our fuel grid, but the road width relative to the fuel load is likely high enough that most stubble burns would be contained by the roads.

Caveats, Assumptions, and Recommendations

As indicated in the introduction section of this report, the BP modeling done in this study is not intended to provide an explicit "probability" of burning. Instead, we have taken an approach that is intended to determine the relative likelihood of burning in one location over another. What this means is that while we may have calculated a raw probability of fire for each pixel of the whole landscape, this value is essentially meaningless: what is important is the relative likelihood of one location versus another location if a crown fire were to occur. We have confidence in these values (ie. one location is 4x more likely to burn than a different location), however even these values assume that the likelihood of fires starting in specific locations follows historical patterns. Essentially this modeling exercise examined how fires spread across the specific Parks Canada jurisdictions included in this study under the following limitations and conditions: a) a single fire burns under a subset of historical weather conditions; b) the subset of weather conditions are days which support the spread of active crown fires in the C3 (Mature Lodgepole Pine) fuel type; c) fires escape initial attack and are free-burning; and d) fires grow and spread for a period of time defined by successive days of active crown-fire supporting weather

Under extreme fire weather conditions, virtually no fuel treatment or sheltering non-fuel patch or previous burn will reduce BP (Miller and Ager 2013). While the areas of elevated BP

around the landscape in complex topography occur in many small pockets and in some larger areas, this does not imply that these are the only areas that would burn if a fire were to occur, and this is the case in general with BP modeling. Fires do not constrain themselves to areas of high BP only, these areas merely indicate where numerous simulated fires tend to aggregate or originate (Parisien et al. 2019), thereby revealing what parts of the landscape are more susceptible to burning than others. Under extreme conditions, fires will burn large tracts that will invariably include substantial areas of moderate to low BP (Parisien et al. 2020).

Another important assumption we must make with BP modeling is that the weather inputs we use are representative of the weather conditions we anticipate for the coming fire seasons. In an era of climate change, this assumption is clearly one that is likely to be violated. Due to this, we chose to use weather conditions that are conducive to crown fire spread to avoid using weather that was too "gentle". There have not been a lot of massive fire years on record in the Rocky Mountains, and therefore if we simply used historical weather and assumed that the distribution of weather indices was acceptable for today's fire conditions, we would likely underestimate fire likelihood by a considerable margin. Even so, by choosing only crown-fire conducive weather in these simulations, we may still be "cooling" the weather too much. We are seeing more and more extreme weather events becoming more common. As Jain et al. (2022) have recently demonstrated, there has been a continuous trend of increasing fire weather indices due to climate change, with a distinct increase in FWI, ISI, and vapour pressure deficit (VPD) over the past 40 years, and while our methods filtered out the low end of the fire weather indices, we likely have not accurately captured the higher end of fire weather danger sufficiently to reflect current fire danger.

Finally, one of the most significant sources of potential error that exists throughout this modeling exercise is the accuracy and currency of the fuel grids used to drive the fire growth models. In the cases of Jasper, Waterton Lakes, and Riding Mountain, we know for certain that the fuel grids are tremendously out of date. Furthermore, in Jasper National Park, the mapping of MPB effects may be sufficient in terms of monitoring the presence, status, and movement of the insect across the landscape, but the attributes that are mapped are insufficient for fire growth modeling. We know that the proportion of dead trees in the stand has a significant

effect on both rate of spread and intensity of fire, and by including everything with 30% or greater mortality in the “severe” category of MPB attack, we are losing a tremendous amount of information on how MPB presence will affect fire as 35% dead will be considerably less dangerous than 45% or 90% for example.

It is our strong recommendation to Parks fire managers that they invest in the necessary surveys (whether on the ground or using remote sensing) to ensure that vegetation maps are current and accurate enough to enable creating fuel grids for fire growth modeling that we can be confident will reflect potential fire behaviour. They also need to ensure that these fuel grid datasets are maintained and kept up to date. This is not to ignore the initiatives underway in numerous parks to use up-to-date aerial imagery, and LIDAR to create new inventories, but methods will need to be standardized and implemented across all parks in order to allow for accurate fire risk modeling.

6. References

Achuff, P.L., Holland, W.D., Coen, G.M., and K. Van Tighem. 1984. Ecological land classification of Kootenay National Park, British Columbia. Vol. I: Integrated Resource Description. Environment Canada, Alberta Institute of Pedology, University of Alberta. Publication M-84-10. 401 pages.

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., Van Wagtendonk, J.W. and C. Weatherspoon. 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecology and Management, 127(1-3):55-66.

Arno, S.F. 1980. Forest fire history in the northern Rockies. Journal of Forestry 8:460–465.

Arno, S.F., and G. Gruell. 1983. Fire history at the forest-grassland ecotone in southwestern Montana. Journal of Range Management 36:332–336

Arno, S., Parsons, D., and R. Keane. 2000. Mixed severity fire regimes in the Northern Rocky Mountains: consequences of fire exclusion and options for the future. USDA Forest Service Proceedings Rocky Mountain Research Station 5:225–232.

Barrett, S.W. 1996. The Historic Role of Fire in Waterton Lakes National Park, Alberta. Technical Report prepared for Parks Canada. 27 pages.

Beaudoin, A., Bernier, P. Y., Guindon, L., Villemaire, P., Guo, X. J., Stinson, G., Bergeron, T., Magnussen, S., and R. Hall. 2014. Mapping attributes of Canada's forests at moderate resolution through kNN and MODIS imagery. Canadian Journal of Forest Research 44:521–532.

Beierle, B. and D.G. Smith. 1998. Severe drought in the early Holocene (10,000-6800 BP) interpreted from lake sediment cores, southwestern Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 140: 75 – 83.

Bergeron, Y., Gauthier, S. Kafka, V., Lefort, P., and D. Lesieur. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustain-able forestry. Canadian Journal of Forest Research 31:384–391.

Beverly, J.L., Herd, E.P.K., and J.C.R. Conner. 2009. Modeling fire susceptibility in west central Alberta, Canada. Forest Ecology and Management. 258: 1465–1478.

Beverly, J.L. 2017. Time since prior wildfire affects subsequent fire containment in black spruce. International Journal of Wildland Fire 26:919–29.

Beverly, J.L., and N. McLoughlin. 2019. Burn probability simulation and subsequent wildfire activity in Alberta, Canada – Implications for risk assessment and strategic planning. Forest Ecology and Management. 451, 117490.

Calkin, D.E., Ager, A.A., and J. Gilbertson-Day. 2010. Wildfire risk and hazard: procedures for the first approximation. General Technical Report RMRS-GTR-235. United States Department of Agriculture Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Campbell, I.D., William, M., Campbell, C., Clare, S. and J.H. McAndrews. 2000. The late-Holocene paleohydrology of Pine Lake, Alberta: a multiproxy investigation. Journal of Paleolimnology 24: 427 – 441.

Chavardes, R.D. and L.D. Daniels. 2016. Altered mixed-severity fire regime has homogenised montane forests of Jasper National Park. International Journal of Wildland Fire 25: 433–444.

Coen, G.M. and P. Kuchar. 1982. Biophysical (Ecological) Inventory of Yoho National Park, British Columbia, Canada. Agriculture Canada, Research Branch, Alberta Institute of Pedology No. M-82-2. 101 pages.

Countryman, C.M. 1972. The fire environment concept. USDA For. Serv. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA. 12 pages.

De Groot, W., Cantin, A., Flannigan, M., Soja, A., Gowman, L., and A. Newbery. 2013. A comparison of Canadian and Russian boreal forest fire regimes. Forest Ecology and Management 294:23–34.

Flatley, W.T., and P.Z. Fule. 2016. Are historical fire regimes compatible with future climate? Implications for forest restoration Ecosphere 7: e01471

Forestry Canada Fire Danger Working Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Headquarters, Fire Danger Group and Science and Sustainable Development Directorate, (Ottawa).

Fortin, J.A., Fisher, J.T., Rhemtulla, J.M., and E. Higgs. 2018. Estimates of landscape composition from terrestrial oblique photographs suggest homogenization of Rocky Mountain landscapes over the last century. Remote Sensing in Ecology and Conservation http://dx.doi.org/10.1002/rse2.100

Giglio, L., Randerson, J.T., van der Werf, G.R., Kasibhatla, P., Colatz, G., Morton, D., and R. DeFries. 2010. Assessing variability and long-term trends in burned area by merging multiple satellite fire products. Biogeosciences 7:1171-1186.

Hallett, D.J., Mathewes, R.W., and R.C. Walker. 2003. A 1000-year record of forest fire, drought and lake-level change in southeastern British Columbia, Canada. The Holocene 13(5): 751 – 761.

Hamann, A., Wang, T., Spittlehouse, D., and T. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94:1307–1309.

Hawkes, B. 1979. Fire history and fuel appraisal of Kananaskis Provincial Park. Prepared for: resource assessment and management section, Planning and Design Branch, Parks Division, Alberta Recreation and Parks. MSc Thesis. University of Alberta, Edmonton, Alberta, USA.

Hawkes, B. 1980. Fire history of Kananaskis Provincial Park - Mean fire return intervals. Pages 42-45 *In*: M.A. Stokes and J.H. Dieterich, technical coordinators. Proceedings of the fire history workshop. October 20-24, Tucson, Arizona, USA. USDA Forest Service, General Technical Report RM-81, Fort Collins, Colorado, USA.

Héon, J., Arseneault, D., and M.-A. Parisien. 2014. Resistance of the boreal forest to high burn rates. Proceedings of the National Academy of Sciences, 111(38): 13888-13893

Hijmans, R.J., Phillips, S., Leathwick, J. and J. Elith. 2020. dismo: Species Distribution Modeling. R package version 1.3-3. https://CRAN.R-project.org/package=dismo

Hijmans, R.J. (2021). raster: Geographic Data Analysis and Modeling. R package version 3.4-10. https://CRAN.R-project.org/package=raster

Hirsch, K. 1996. Canadian forest fire behavior prediction (FBP) system: user's guide. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

Holland, W.D. and G.M. Coen. 1982. Ecological (Biophysical) Land Classification of Banff and Jasper National Parks. Vol II: Soil and Vegetation Resources. Environment Canada, Alberta Institute of Pedology, University of Alberta. Publication M-83-2. 624 pages.

Jain, P., Castellanos-Acuna, D., Coogan, S.C.P., Abatzoglou, J.T., and M. Flannigan. 2022. Observed increases in extreme fire weather driven by atmospheric humidity and temperature. Nature Climate Change 12, 63–70

Janz, B. and D. Storr. 1977. The Climate of the Continuous Mountain Parks. Atmospheric Environment Services. Project Report No. 30. Toronto, ON. 324 pages.

Johnson, E.A., and C.P.S. Larsen. 1991. Climatically induced change in fire frequency in the Southern Canadian Rockies. Ecology 72 (1): 194 – 201.

Johnson, E.A. 1996. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University Press.

Kasischke, E., and M. Turetsky. 2006. Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters 3:1-5.

Keane, R.E., Ryan, K.C., Veblen, T.T., Allen, C.D., Logan, J., and B. Hawkes. 2002. Cascading effects of fire exclusion in Rocky Mountain ecosystems: a literature review. USDA Forest Service General Technical Report RMRS-GTR-91. Fort Collins, CO.

Kubian, R. 2013. Characterizing the mixed-severity fire regime of the Kootenay Valley, Kootenay National Park. M.Sc. Thesis. University of Victoria, BC. 112 pages.

Kuhn, M. (2021). caret: Classification and Regression Training. R package version 6.0-88. https://CRAN.R-project.org/package=caret

Liaw, A. and M. Wiener. 2002. Classification and Regression by randomForest. R News 2(3), 18--22.

Lentile, L.B., Morgan, P., Hudak, A.T., Bobbitt, M.J., Lewis, S.A., Smith, A.M.S., and P.R. Robichaud. 2007. Post-Fire Burn Severity and Vegetation Response Following Eight Large Wildfires Across the Western United States. Fire Ecology 3, 91–108

MacDonald, G.M. 1989. Postglacial palaeoecology of the subalpine forest grassland ecotone of southwestern Alberta: new insights on vegetation and climate change in the Canadian

Rocky Mountains and adjacent Foothills. Palaeogeography, Palaeoclimatology, Palaeoecology 73: 155 – 173.

MacKillop, D.J., Ehman, A.J., Iverson, K.E., and E.B. McKenzie. 2018. A field guide to site classification and identification for southeast British Columbia: The East Kootenay. Prov. B.C., Victoria, B.C. Land Management Handbook 71

Marcoux, H.M., Daniels, L.D., Gergel, S.E., Da Silva, E., Gedalof, Z., and P.F. Hessburg. 2015. Differentiating mixed- and high-severity fire regimes in mixed-conifer forests of the Canadian Cordillera. Forest Ecology and Management 341: 45 – 58.

Masters, A.M. 1990. Changes in forest fire frequency in Kootenay National Park, Canadian Rockies. Canadian Journal of Botany 68: 1763-1767.

Merrill, D.F., and M.E. Alexander (eds). 1987. Glossary of forest fire management terms. Fourth edition. Canadian Committee on Forest Fire Management, National Research Council of Canada, Ottawa, Ontario.

Miller, C., Parisien M.-A., Ager, A., and M. Finney. 2008. Evaluating spatially explicit burn probabilities for strategic fire management planning. Modeling, Monitoring and Management of Forest Fires 1:245–252.

Miller, C., and A. Ager. 2013. A review of recent advances in risk analysis for wildfire management. International Journal of Wildland Fire 22:1–14.

Natural Regions Committee 2006. Natural Regions and Subregions of Alberta. Compiled by D.J. Downing and W.W. Pettapiece. Government of Alberta. Pub. No. T/852.

Natural Resources Canada. 2020. Canadian large fire database. [online] available at http://cwfis.cfs.nrcan.gc.ca/datamart

Parisien, M.-A., Kafka, V. Hirsch, K., Todd, J., Lavoie, S., and P. Maczek. 2005. Mapping wild-fire susceptibility with the BURN-P3 simulation model. Information Report NOR-X-405. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada.

Parisien, M.-A., Junor, D., and V. Kafka. 2007. Comparing landscape-based decision rules for placement of fuel treatments in the boreal mixedwood of western Canada. International Journal of Wildland Fire 16:664–672.

Parisien M.-A., Parks, S., Miller, C., Krawchuk, M., Heathcott, M., and M. Moritz. 2011. Contributions of ignitions, fuels, and weather to the spatial patterns of burn probability of a boreal landscape. Ecosystems 14:1141–1155.

Parisien, M.-A., Walker, G., Little, J., Simpson, B., Wang, X., and D. Perrakis. 2013. Considerations for modeling burn probability across landscapes with steep environmental gradients: an example from the Columbia Mountains, Canada. Natural Hazards 66, 439–462.

Parisien, M.-A., Dawe, D.A., Miller, C., Stockdale, C.A., and O.B. Armitage. 2019. Applications of simulation-based burn probability modelling: a review. International Journal of Wildland Fire. Early Online. https://doi.org/10.1071/WF19069.

Parisien, M.A., Ager, A., Barros, A., Dawe, D., Erni, S., Finney, M., McHugh, M., Miller, C., Parks, S., Riley, K., Short, K., Stockdale, C., Wang, X., and E. Whitman. 2020. Commentary on the article "Burn probability simulation and subsequent wildland fire activity in Alberta, Canada – Implications for risk assessment and strategic planning" by J.L. Beverly and N. McLoughlin. Forest Ecology and Management 450(16): article 117698.

Parks, S.A. 2014. Mapping day-of-burning with coarse-resolution satellite fire-detection data. International Journal of Wildland Fire 23:215-223.

Parks, S.A., Miller, C., Holsinger, L.M., Baggett, L.S., and B. Bird. 2016. Wildland fire limits subsequent fire occurrence. International Journal of Wildland Fire 25:182–90.

Peel, M.C., Finalyson, B.L., and T.A. McMahon. 2007. Updated world map of the Koppen-Geiger climate classification. Hydrology and Earth System Sciences 11:1633-1644.

Perrakis, D., Eade, G., and D. Hicks. 2017. British Columbia wildfire fuel typing and fuel type layer description. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-144.

Prichard, S.J., Hessburg, P., Gray, R., Povak, N., Solter, B., Stevens-Rumann, C. and P. Morgan. 2018. Final Report: evaluating the influence of prior burn mosaics on subsequent wildfire behavior, severity, and fire management options. Joint Fire Science Project 14_1_02_30.

Rhemtulla, J.M., Hall, R., Higgs, E., and S.E. Macdonald. 2002. Eighty years of change: Vegetation in the montane ecoregion of Jasper National Park, Alberta, Canada. Canadian Journal of Forest Research. 32: 2010–2021.

Rogeau, M-P. 1994a. Fire History Study of the Spray Lakes Area, Alberta. Central Rockies Ecosystem Inter-agency Liaison Group, Operation Branch, Kananaskis Country. 12 pages. + one map sheet.

Rogeau, M-P. 1994b. Fire History Study of Mount Assiniboine Provincial Park, British-Columbia. Central Rockies Ecosystem Inter-agency Liaison Group, Operation Branch, Kananaskis Country. 15 pages + one map sheet.

Rogeau, M-P. and D. Gilbride. 1994. Stand origin mapping of Banff National Park. Technical report prepared for Banff National Park, Resource Conservation Branch, Banff, AB, Canada. 70 pages + 8 map sheets.

Rogeau, M-P. 1996. Understanding age-class distributions in the Southern Canadian Rockies. M.Sc. Thesis. University of Alberta, Edmonton, AB, Canada. 139 pages.

Rogeau, M-P. 1999. Fire history study of the Central Rockies Ecosystem Inter-Agency North-Saskatchewan Unit. Technical report prepared for Banff National Park, Box 900, Banff, AB. T0L 0C0. 61 pages.

Rogeau, M-P., Pengelly, I. and M-J. Fortin. 2004. Using a topography model to map historical fire cycles and monitor current fire cycles in Banff National Park. Pages 55-69 *In*: R.T. Engstrom, and W.J. de Groot, editors. Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in Temperate, Boreal, and Montane ecosystems. Tall Timbers Research Station, Tallahassee, Florida, USA.

Rogeau, M-P. 2005. Fire history study - Kananaskis District Alberta - 2004 field results. Technical report prepared for Spray Lake Sawmills Ltd., Cochrane; Alberta Sustainable Resource Development, Calgary; and Alberta Community Development - Parks and Protected Areas, Canmore, Canada. 67 pages.

Rogeau, M-P. 2006. Fire history study - Kananaskis District Alberta - 2005 field results. Technical report prepared for Spray Lake Sawmills Ltd., Cochrane; Alberta Sustainable Resource Development, Calgary; and Alberta Community Development - Parks and Protected Areas, Canmore, Canada. 40 pages.

Rogeau, M-P. 2010. Part II - Fire history study 2009 field results, FMU R11. Technical report prepared for Alberta Sustainable Resource Development, Forest Protection Branch, Rocky Mountain House, AB, Canada. 95 pages.

Rogeau, M-P. 2011a. Fire history study SLS FMA - South of the Highwood River, Alberta. Technical report prepared for Spray Lake Sawmills Ltd, Cochrane, AB, Canada. 42 pages.

Rogeau, M-P. 2011b. Fire history study of the Elbow Fire Management Compartment, Alberta. Technical report prepared for Alberta Sustainable Resource Development, Forest Protection Branch, Southern Rockies Area, Calgary, Canada. 57 pages.

Rogeau, M-P. 2012. Fire history study Castle River Watershed, Alberta. Technical report prepared for Alberta Environment and Sustainable Resource Development, Forest Protection Branch, Southern Rockies Wildfire Management Area, Calgary, AB, Canada. 54 pages.

Rogeau, M-P. 2014. Fire history of the Porcupine Hills, Alberta. Technical report prepared for Alberta Environment and Sustainable Resource Development, Forest Protection Branch, Southern Rockies Wildfire Management Area, Calgary, Alberta, Canada. 56 pages.

Rogeau, M-P., Flannigan, M., Hawkes, B., Parisien, M.-A. and R. Arthur. 2016. Spatial and temporal variations of fire regimes in the Canadian Rocky Mountains and foothills of southern Alberta. International Journal of Wildland Fire 25(11):1117-1130.

Rogeau, M-P. and G.W. Armstrong. 2017. Quantifying the effect of elevation and aspect on fire return intervals in the Canadian Rocky Mountains. Forest Ecology and Management 384: 248-261.

Rollins, M.G., Morgan, P., and T. Swetnam. 2002. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landscape Ecology 17: 539-557.

Schwartz, M.W., Butt, N., Dolanc, C., Holguin, A., Moritz, M., North, M., Safford, H., Stephenson, J., Thorne, J. and P.J. van Mantgem. 2015. Increasing elevation of fire in the Sierra Nevada and implications for forest change. Ecosphere 6(7) doi:10.1890/ES15-00003.1.

Schweger, C.E. and M. Hickman. 1989. Holocene paleohydrology of central Alberta: testing the general-circulation-model climate simulations. Canadian Journal of Earth Science. 26: 1826 – 1833.

Scott, J., Thompson, M., and D. Calkin. 2013. A wildfire risk assessment framework for land and resource management. General Technical Report RMRS-GTR-315. United States Department of Agriculture Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Sherriff, R.L., Veblen, T.T., and J.S. Sibold. 2001. Fire history in high elevation subalpine forests in the Colorado Front Range. Ecoscience 8(3): 369-380.

Sibold, J.S., Veblen, T.T., and M.E. Gonzalez. 2006. Spatial and temporal variation in historic fire regimes in subalpine forests across the Colorado Front Range in Rocky Mountain National Park, Colorado, USA. International Journal of Biogeography 33(4): 631-647.

Stephens, S.L., Burrows, N., Buyantuyev, A., Gray, R., Keane, R., Kubian, R., Liu, S., Seijo, F., Shu, L. and K.G. Tolhurst. 2014. Temperate and boreal forest mega-fires: characteristics and challenges. Frontiers in Ecology and Environment. 12: 115–122.

Stockdale, C.A., McLoughlin, N., Flannigan, M., and S.E. Macdonald. 2019a. Could restoration of a landscape to a pre-European historical vegetation condition reduce burn probability? Ecosphere 10: e02584

Stockdale, C.A., Macdonald, S.E., and E. Higgs. 2019b. Forest closure and encroachment at the grassland interface: a century-scale analysis using oblique repeat photography. Ecosphere 10(6): e02774

Stockdale, C., Barber, Q., Saxena, A., and M. Parisien. 2019c. Examining management scenarios to mitigate wildfire hazard to caribou conservation projects using burn probability modeling. Journal of Environmental Management. 233: 238–248.

Stocks, B.J., Mason, J., Todd, J., Bosch, E., Wotton, B., Amiro, B., Flannigan, M., Hirsch, K., Logan, K., Martell, D., and W. Skinner. 2002. Large forest fires in Canada, 1959–1997. Journal of Geophysical Research: Atmospheres, 107(D1).

Thompson, M., Calkin, D., Finney, M., Ager, A., and J. Gilbertson-Day. 2011. Integrated national-scale assessment of wildfire risk to human and ecological values. Stochastic Environmental Research and Risk Assessment 25: 761–780.

Tymstra, C., Bryce, R., Wotton, M., Taylor, S., and O.B. Armitage. 2010. Development and structure of Prometheus: the Canadian Wildland Fire Growth Simulation Model. Information Report NOR-X-417. Natural Resources Canada, Canada Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada.

Van Wagner, C.E., Finney, M.A., and M. Heathcott. 2006. Historical fire cycles in the Canadian Rocky Mountain parks. Forest Science. 52(6):704 – 717.

Vance, R.E., Emerson, D., and T. Abgoo. 1983. A mid-Holocene record of vegetative change in central Alberta. Canadian Journal of Earth Science 20:364 – 376.

Wang, X., Parisien, M., Flannigan, M., Parks, S., Anderson, K., Little, J., and S. Taylor. 2014. The potential and realized spread of wildfires across Canada. Global Change Biology 20:2518–2530.

Wang, X., Parisien, M.-A., Taylor, S., Perrakis, D., Little, J., and M. Flannigan. 2016. Future burn probability in south-central British Columbia. International Journal of Wildland Fire 25:200–212.

Wang, X., Parisien, M.-A., Taylor, S., Candau, J.-N., Stralberg, D., Marshall, G., Little, J., and M. Flannigan, M. 2017. Projected changes in daily fire spread across Canada over the next century. Environmental Research Letters 12(2):025005.

Werth, P.A., Potter, B.E., Clements, C., Finney, M., Goodrick, S., Alexander, M., Cruz, M., Forthofer, J. and S. McAllister. 2011. Synthesis of knowledge of extreme fire behavior: volume I for fire managers. USDA For. Ser., Pacific Northwest Research Station, Portland, OR General Technical Report PNW-GTR-854.

White, C.A. 1985a. Fire and biomass in Banff National Park closed forests. M.Sc Thesis. Colorado State University, Fort Collins, CO. U.S.A. 205 pages.

White, C. 1985b. Wildland fires in Banff National Park, 1880-1980. Occasional Paper No.3. National Parks Branch, Parks Canada, Environment Canada. Catalogue No.: R61 2/8- E. 108 pages.

Whitman, E., Parisien, M., Price, D., St-Laurent, M., Johnson, C., DeLancey, E., Arseneault, D., and M. Flannigan. 2017. A framework for modeling habitat quality in disturbance-prone areas demonstrated with woodland caribou and wildfire. Ecosphere 8(4): e01787.

Wierzchowski, J., Heathcott, M., and M. Flannigan. 2002. Lightning and lightning fire, Central cordillera, Canada. International Journal of Wildland Fire, 11: 41 – 51.