Spring wildfires in Alberta and opportunities for enhanced wildfire preparedness

by

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Abstract

Canada is a forest nation shaped by recurring wildfires which on average burn 2.25 Mha yr^{-1} (1970 – 2019). Most of this burned area occurs within the boreal zone which extends across Canada from Yukon to Newfoundland and Labrador. The year-to-year area burned is highly variable ranging from 289,000 ha in 1978 to 7.56 million ha in 1989. In the last two decades western Canada has experienced the most disastrous wildfire seasons (insured losses). While the number of wildfires in Canada are decreasing, the area burned is increasing. As the frequency of large, high intensity wildfires increase, their social, economic and ecological impacts will become increasingly more challenging to manage.

To balance the positive and negative impacts of wildfire, agencies implement six phase phases of wildfire management (prevention, mitigation, preparedness, response, recovery and review) based on their program strategies and policies. Preparedness is a critical phase and the focus of this thesis because agencies cannot effectively manage wildfires if they are not ready (prepared).

The recent disastrous spring wildfires in Alberta motivated my interest to understand why this province continues to experience challenging wildfires despite implementing recommendations from six wildfires reviews since 1998. In Chapter 2 of this thesis I used twelve semi-structured interviews with five open thematic questions. Canadian Interagency Forest Fire Centre Fire Science Committee agency representatives were purposively sampled to compile agency information on their i) organizational structure and role, ii) wildfire management strategy, iii) preparedness level determination, iv) fire weather and fire behavior advisories and/or warnings, and v) regulatory tools used to prevent wildfires. Results indicate that although all wildfire

management agencies use the Canadian Forest Fire Danger Rating System there are considerable differences in how they determine their preparedness level, and the level of decision support (tools) they use to make these determinations. There is also no national standard for fire weather and fire behavior advisories and warnings. Fire bans are the preferred regulatory tool followed by use restrictions and area closures.

Chapter 2 includes a wildfire management paradigm shift. This proposed shift in managing wildfires recognizes that is not ecologically desirable nor economically feasible to remove all wildfire from fire-dependent ecosystems. To coexist with wildfire, agencies need to strengthen and adjust their capacity and capability to support more managed wildfire on the landscape.

Chapter 3 was inspired when I learned how syndromic biosurveillance and statistical visualization tools are used in health sciences to forecast disease outbreaks and provide situational awareness. Statistical surveillance thresholds of initial attack (IA) and being held (BH) escapes were developed for situational awareness of spring wildland fire activity in Alberta. These thresholds when combined with the tracking of sea surface temperature anomalies (El Niño) can provide additional support in real time as part of an early warning system of wildfire risk.

In Chapter 4 the synoptic surface and upper (500 hPa) weather patterns, and fire weather indices were evaluated for the first four days of wildfire growth for 80 large wildfires that started in May and grew over 1,000 ha in size. Pre-frontal and frontal activity are associated with 48% of the calendar spread days. Dry Arctic air masses creating strong south-southeast winds are associated with 26% of the calendar spread days. Fine Fuel Moisture Code (FFMC) and Initial Spread Index (ISI) vary significantly between spread days and non-spread days. Spring wildfires in Alberta are wind driven and characterized by very high to extreme FFMC and ISI values; however, very high to extreme Buildup Index (BUI) values are not a perquisite for extreme spring wildfire behavior.

May wildfires account for 23% of all wildfires but are responsible for 55% of the total area burned (March 1 – October 31). Opportunities for enhanced wildfire preparedness include the increased use of regulatory tools, night-time surveillance, integration of weather and fire behavior services, import of resources for preparedness, and the use of statistical visualization tools such as attribute control charts.

Preface

Chapter 2 of this thesis is a slightly modified version of the paper published as C. Tymstra, B.J. Stocks, X. Cai, and M.D. Flannigan, "Wildfire management in Canada: Review, challenges and opportunities", *Progress in Disaster Science*, vol. 5, (2020) 100045. Cordy Tymstra designed the survey of wildfire management agencies across Canada, and completed the analysis of the interviews. X. Cai assisted with the agency interviews and audio transcriptions. The data analysis and manuscript composition were completed by Cordy Tymstra. B.J. Stocks and M.D. Flannigan provided manuscript edits. Kimberly Morrison (formerly with Alberta Agriculture and Forestry) provided assistance with the completion of the maps. GIS data were provided by the agencies. The research conducted for this chapter required ethics approval.

Chapter 3 of this thesis is a slightly modified version of the paper published as C. Tymstra, D.G. Woolford, and M.D. Flannigan, "Statistical surveillance thresholds for enhanced situational awareness of spring wildland fire activity in Alberta, Canada", *Journal of Environmental Statistics* vol. 9, issue 4. D.G. Woolford and M.D. Flannigan provided manuscript edits.

Chapter 4 of this thesis is a slightly modified version of the manuscript submitted to the International Journal of Wildland Fire as C. Tymstra, P. Jain and M.D. Flannigan "Characterization of initial fire weather conditions for large spring wildfires in Alberta, Canada". Jain obtained and processed the ERA5 reanalysis data, and assisted with the editing and layout of the manuscript. The data extraction from the grids were completed by C. Tymstra. All other data analysis and manuscript composition were completed by C. Tymstra. M.D. Flannigan provided manuscript edits.

Dedication

This thesis is dedicated to my wife Hua Sun who patiently supported me, and at times tolerated my journey of learning and pursuit of science. She too worked in Alberta's Wildfire Management Branch and understood my passion and desire to contribute to advance wildfire management in Canada.

Acknowledgements

I was fortunate to have access to committee members with a diverse range of skills, experience and knowledge. Collectively, my committee remarkably offered over 100 years of wildland fire experience and knowledge. I am thankful for their help and encouragement during my long journey to the finish line. I also thank all of the wildfire management agencies for participating in interviews and sharing data and information not available in the published literature. Colleagues in Alberta's Wildfire Management Branch where I worked were very helpful and supportive. I was always learning from them.

Despite his very busy schedule, demands from the media around the world, and a growing Canada Wildfire partnership based at the University of Alberta, my supervisor Dr. Mike Flannigan always found time to talk with me when I needed guidance. Dr. Flannigan's expertise in fire weather and climate change is world renown. This was a great resource that I and other graduate and non-graduate students were able to access.

Dr. Douglas Woolford is one of the few environmental statisticians I know who has fostered and sustained strong relationships with wildfire management agencies, particularly with Ontario and Alberta. He influenced my shift in statistics thinking and application from classical data analysis to exploratory data analysis. Agencies need more people like Dr. Woolford to help solve today's wildfire management challenges.

Mr. Brian Stocks retired after working 35 years as a research scientist for the Canadian Forest Service. Retirement though did not stop Mr. Stocks from continuing to work and support wildfire management in Canada and around the world. He recognized the need to conduct experimental research burns to support the early development of the Canadian Forest Fire Danger Rating System. Mr. Stocks understands the importance of building relationships; researchers learning from agency field staff, and these agency field staff learning the importance of fundamental research to support wildfire science and operational decision making. He has a broad understanding of the issues confronting wildfire management agencies today and the need to be prepared for emerging issues. I was fortunate to have Mr. Stocks on my committee. His experience and knowledge in wildfire behavior was recognized in 2017 when he received the International Association of Wildland Fire Ember Award for excellence in wildfire science.

Mr. Stocks' passion for fire science and his advocacy for governments to support wildfire science are inspirational. His calming and continuing words of encouragement helped me on my marathon run to complete this thesis.

The late Peter J. Murphy was a huge inspiration for me. He was my MSc supervisor at the University of Alberta. He completed his PhD at the University of British Columbia later in his life. I followed in his footsteps and also began my PhD studies later in my career. Dr. Murphy was always learning, always teaching, and always helping others.

I am thankful for the support from the Alberta Wildfire Management Branch to cover part of my education costs while I was still working for the branch. I hope that other staff within the branch who are interested in learning throughout life may also have similar opportunities to advance their education and contribute to continuing excellence in wildfire management in Alberta.

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1. Introduction

1.1 Background

In 1987, the Brundtland Report of the World Commission on Environment and Development introduced the theme of sustainable development (Brundtland 1987). This report recognized the need for natural ecological systems to sustain the health of the planet, and that without a healthy environment, sustainable development cannot be achieved. The United Nations General Assembly endorsed the Brundtland Report and five years later sponsored another conference, known as the “1992 Earth Summit”. This conference resulted in the signing of international agreements on biological diversity, climate change and forests. Although the statement of principles on forests was a non-binding agreement, it represented the first attempt to address forest issues from a global perspective.

The Canadian ministers responsible for forestry endorsed the goal of sustainable forest management by signing and committing to a five year National Forest Strategy in 1992. This action plan set out a framework based on nine strategic directions, each with guiding principles, objectives and a list of actions. The strategic direction of forest stewardship included the goal of reducing wildfire losses and managing the economic, social and ecological impacts of wildfire. To achieve this, wildfire management agencies needed to improve their capabilities to spatially and temporally determine the appropriate level and type of protection against wildfire, while also recognizing the natural role of wildfire in maintaining healthy forest ecosystems.

Managing the economic, social and ecological impacts of wildfire has been a challenge since the “1992 Earth Summit”. As noted by Weber and Stocks (1998), it is not economically feasible nor ecologically desirable to remove all wildfires from the boreal forest. Making an appropriate response decision to balance the impacts of wildfire (positive and negative) while also managing costs, requires decision support tools. Ontario for example developed a risk assessment system with a suite of models including RamPART (Resources and Assets iMPAct Relative Total) which quantifies total impacts systematically and consistently (McFayden et al. 2019).

RamPART focuses on the negative impacts of wildfire; incorporating the positive impacts (ecological benefits) remains a challenge.

Forests cover 38% of Canada's land surface. This equates to approximately 347 million hectares or 9% of the world's forests (Natural Resources Canada 2020). Canada is known as a forest nation, but it is also a country of forests that have evolved with the cyclic disturbance of wildfire. Most (90 %) of Canada's forests are on public lands. A very small portion of Canadian forests are harvested each year. In 2018 for example, 0.2% of the total forested area in Canada was harvested. In comparison, wildfires burned 0.5% for the same year. On average, approximately 7,900 wildfires occurred and burned 2.25 million ha in Canada during the 1970 – 2919 period. The area burned is highly variable ranging from 289,157 ha in 1978 to 7,559,572 ha in 1989.

Most of the disastrous wildfires in the last two decades have occurred in western Canada. On May 27 – 28, 2001, the Chisholm Wildfire made a 35 km northwest run towards the Town of Slave Lake, Alberta. Most of the ten homes and 48 outbuildings destroyed by the wildfire were in the Hamlet of Chisholm located 56 km southeast of Slave Lake. This was the first wildfire in Alberta with significant structural losses since the Great Wildfire of 1919 when the Town of Lac La Biche was destroyed (Murphy et al. 2015). The Chisholm Fire Review Committee concluded that despite Alberta generally having a very effective wildfire suppression program, a small percentage of wildfires continue to escape initial attack efforts and become large in size. (Chisholm Fire Review Committee 2001). The review committee's final report included five recommendations to address issues and improvement opportunities with communications, unified planning and interagency coordination, community protection, and presuppression planning and suppression for existing and anticipated extreme fire conditions.

The key presuppression planning issue identified by the Chisholm Fire Review Committee is relevant to this thesis which focuses on spring wildfires in Alberta. Because of the extremely dry spring conditions the review committee suggested there was a missed opportunity to adjust strategy and tactics. More needed to be done to address the current and forecasted extreme wildfire behavior because the standard operating procedures were not appropriate during extreme fire weather conditions. The review committee recommended the use of forest closures or restrictions, improved detection and monitoring (including night time surveillance) and prevention of human-caused wildfires.

Two years after the Chisholm Wildfire in Alberta, the Okanagan Mountain Park Wildfire in the neighbouring Province of British Columbia destroyed 239 homes and forced the evacuation of 27,000 residents. After the disastrous 2003 wildfire season, discussions began regarding the need for a separate wildfire strategy in Canada. Wildfire management agencies across Canada recognized the need for a shared vision to address a declining suppression capacity. The agencies identified the need to strengthen hazard mitigation, preparedness and recovery to ensure they are able to confront a future with more wildfire.

In October 2005 the federal, provincial, and territorial forest ministers signed a declaration to commit to supporting a common set of principles and goals in a new Canadian Wildland Fire Strategy (CWFS) (Canadian Council of Forest Ministers 2005). A status of the CWFS was summarized in an update report in 2008 which highlighted some accomplishments but stated that progress was too slow, in part, because implementation of the CWFS is costly. The CWFS was updated in 2016 as part of a 10-year review and renewed call for action (Canadian Council of Forest Ministers Wildland Fire Management Working Group 2016a). That year, Canada experienced another disastrous wildfire season when the Horse River Wildfire in northeast Alberta burned through the Urban Service Area of Fort McMurray. This became the costliest natural disaster in Canadian disaster with $3.84 billion in insured losses.

The 10-year review and renewed call to action of the CWFS identified the actions to continue to move forward with the strategy (Canadian Council of Forest Ministers Wildland Fire Management Working Group 2016a). These actions include:

- enhancing horizontal collaboration and integration;
- increasing investment in innovation;
- enhancing prevention and mitigation capability;
- enhancing commitment to FireSmart and,
- increasing preparedness capacity.

The renewed call to action suggests preparedness capacity can be achieved by enhancing firefighting capacity, and upgrading highly qualified personnel, aircraft, and equipment. In anticipation of wildfire arrivals, wildfire management agencies move their firefighting assets focusing on those areas with the highest risk (high values-at-risk, high wildfire occurrence potential, and high wildfire behavior potential).

Preparedness is an important phase of emergency management. Also known as disaster management, emergency management is a function guided by the concept of a shared responsibility and common approach to manage all-hazards emergencies. To facilitate the implementation of this approach across Canada, federal, provincial and territorial governments in Canada collaboratively developed the Emergency Management Framework (EMF) for Canada (Public Safety Canada 2017). This framework defines preparedness as:

"To be ready [readiness or preparedness] to respond to a disaster and manage its consequences through measures taken prior to an event, for example emergency response plans, mutual assistance agreements, resource inventories and training, equipment and exercise programs."

Preparedness in the context of wildfire management is defined in the Canadian Wildland Fire Glossary (Canadian Interagency Forest Fire Centre 2021a) as:

"Actions that involve a combination of planning, resources, training, exercising, and organizing to build, sustain, and improve operational capabilities. Preparedness is the process of identifying the personnel, training, and equipment needed for a wide range of potential incidents, and developing jurisdiction-specific plans for delivering capabilities when needed for an incident."

The condition or degree of being able and ready to cope with an anticipated fire situation is reported by wildfire management agencies as a preparedness level. The Canadian Interagency Forest Fire Centre (CIFFC) reports the daily preparedness level for each agency in a report called the National Wildland Fire Situation Report. The five preparedness levels included in the national report are based on category ratings of six reported criteria: agency fire danger, current fire load, anticipated fire load (7 day), agency resource levels, agency's ability to respond to CIFFC resource requests, and potential for international assistance (Canadian Interagency Forest Fire Centre 2021b).

Wildfire managers make decisions based on anticipated (preparedness) and actual (response) resource needs. When resource need exceeds resource availability, wildfire managers seek assistance from other agencies across Canada or other countries. No one agency has sufficient resources to manage large surges in resource demand. For instance, Alberta had 316 wildfire starts from May 27 to June 17, 1995. During this time, the average Buildup Index (BUI), a relative measure of the amount of fuel available for combustion was 120 (extreme category). The maximum BUI value of 180 was reached at High Level in northwest Alberta. The average BUI last exceeded these levels in the 1930s, when major wildfires burned extensive areas of the Eastern Slopes of Alberta. Of the 316 wildfire starts, 266 were controlled in 24 hours or less. Only 8 (2.5%) wildfires burned uncontrolled for more than four days. 1995 became the worst wildfire season since 1982 when 55 Class E wildfires (> 200 ha) occurred.

The spring of 1998 surpassed 1995 to become the next worst season in Alberta. From January 1 to April 30, 154 wildfire starts occurred. Over the next two months, 656 new wildfire starts burned a total of 369,891 ha. At one point, eleven communities were threatened resulting in the evacuation of several communities. A very strong El Niño occurred during the winter/spring of 1997/1998. This was evident in the BUI which was over 90 in central Alberta during the first week of May.

Another surge of wildfires during the spring occurred during the period May 11 – 15, 2011, when Alberta had 189 new wildfire starts in addition to 22 wildfires already burning. Fifty-two of these wildfires occurred in the Lesser Slave Area where on May 15, one of the 114 active wildfires on that day entered the Town of Slave Lake causing considerable destruction.

Since becoming established in 1982, CIFFC has assisted its member agencies when they are confronted with challenging wildfire seasons and resource demand exceeds their resource availability, by coordinating the sharing of resources across Canada under the Mutual Aid Resource Sharing Agreement and between countries under various international agreements. For example, from when ten firefighting crews and two Incident Management Team personnel were mobilized to Alberta on May 20, 2015. Later in the wildfire season Alberta sent two air tankers and one birddog aircraft to the United States. These resources were returned to Alberta on September 9th.

CIFFC also facilitates information sharing, and coordinates and supports the development of national training courses and standards. More recently CIFFC is becoming more engaged in the national coordination of strategic wildfire management planning, and wildfire mitigation and prevention initiatives.

The exchange of resources across Canada through CIFFC has predominantly supported sustained action (i.e. existing large wildfires). Although importing resources to support preparedness (i.e. anticipating wildfire arrivals) seldom occurs, it is an opportunity for wildfire management agencies to position themselves at higher levels of preparedness. This strategy recognizes that successful initial attack yields the highest return on investment.

Preparedness is more than just prepositioning the right number and type of resources with corresponding readiness or alert levels. The following eight components influence the preparedness capability of a wildfire management organization (modified from Huder 2012):

- Strategic Planning (1 – 5 years)
    - Wildfire management strategy, policy and procedures
    - Regional, sub-regional and area wildfire management plans
    - Wildfire prevention plans
    - Wildfire mutual aid agreements, control agreements, and control plans

- Strategic Planning (5 – 10+ days)
    - 5 – 10 day situational awareness
    - 10+ day and seasonal situational awareness

- Tactical Planning (1 – 3 days)
    - Daily presuppression plans
    - Daily detection plans
    - Regulatory tools (fire bans, area closures etc.)

- Equipment
    - Maintenance, testing and upgrading
    - Appropriate inventory (type and number) and location

- Staff Competencies

    - Training (courses) and certification
    - Table-top exercises

- Education
    - Public
    - Industry

- Enforcement
    - Act and regulations

- Communication, Cooperation, Coordination, and Collaboration (4 Cs)
    - Multi-agency partnering and integration

Alberta's Wildfire Management Branch maintains a distinction between preparedness for initial attack and preparedness for expanded attack and sustained action. This ensures resources are available to initial attack new arrivals (considered as the first priority), and are not diverted to support suppression activities on wildfires that already escaped initial attack. Initial attack resources are prepositioned within Alberta's ten Wildfire Management Areas based on coverage assessments calculated by a program called AWARE (Alberta Wildfire Anticipation and Readiness Engine). The objective is to strategically position initial attack resources to reduce travel times to potential wildfire starts. Coverage is attained if positioned initial attack resources are able to arrive at hypothetical wildfires located in each raster cell in AWARE's database before the simulated wildfire growth exceeds 2 ha in size.

How agencies across Canada prepare for the arrival of wildfires is summarized and discussed in Chapter 2. Semi-structured interviews with wildfire management agencies were conducted to understand the strategies, policies, preparedness procedures, and decision support systems and tools they use to prepare for wildfires starts and manage them when they do arrive. To co-exist with wildfire, agencies in Canada need to adopt a fundamental change in approach and practice to manage wildfires and coexist with a future with more wildfire on the landscape. This paradigm shift (see Fig. 2.5) is described in more detail in Chapter 2. Chapter 5 provides examples of opportunities to enhance wildfire preparedness to achieve implementation of the paradigm shift.

Chapter 3 introduces an approach to enhance situational awareness of potential spring wildfire activity in Alberta that uses syndromic surveillance with statistical thresholds. Syndromic surveillance uses nowcasting data to continuously monitor, analyze, and detect event change signals. This chapter uses initial attack (IA) and being-held escape surveillance charts in near-real time with thresholds as decision support for enhancing and tracking situational awareness. Preceding December sea surface temperatures (SST) of the Pacific Ocean were also used as an indicator of persistence of spring wildfire activity. The hypothesis states "daily tracking of IA and BH escapes and SST provides additional (enhanced) decision support for preparedness". This surveillance is part of an overall early warning system of spring wildfire risk.

The motivation for developing statistical wildfire surveillance thresholds was the i) extensive application of biosurveillance and statistical visualization techniques in health sciences to forecast disease outbreaks, and ii) access to near-real time wildfire data in Alberta (see Section 1.2). Real-time wildfire data entered into a system called FIRES (Fire Information Resource Environment System) is currently not used to its full potential nor is it well integrated with other applications to support preparedness in the same way real time data is used in health sciences for biosurveillance. There are opportunities to analyze and interpret FIRES data and other wildfire environment data using statistical visualization tools.

Fuel, weather and topography and their interactions are the main variables influencing wildfire behavior. Weather is the most variable factor because the atmosphere is three dimensional and in constant motion. Spring wildfires in Alberta are mostly wind-driven. Chapter 4 investigates the initial fire weather conditions for large wildfires in Alberta that started in May and grew to over 1,000 ha in extinguished size. This chapter addresses the hypothesis that the synoptic surface and upper (500 hPa) weather patterns associated with the 1968 wildfire outbreak are repeated and predominate patterns in Alberta during the spring when large wildfires occur. The initial four days of wildfire spread are characterized by synoptic weather patterns and fire weather/danger based on the Canadian Forest Fire Weather Index System outputs (Stocks et al. 1989).

Three themes thread through the core chapters of this thesis. The first theme is the increasing challenges confronting wildfire management agencies in Canada to cope with a future landscape with more intense and severe wildfire. The second theme is agency wildfire preparedness which is a state of readiness in anticipation of wildfire arrivals. The last theme is the opportunities for agencies to be better prepared to manage wildfires and mitigate their destructive impacts. Chapters 3 and 4 focus on spring wildfires in the Province of Alberta. Although spring wildfires occur across Canada, the spring wildfire season in Alberta has resulted in the most damage to communities. The recommendations for enhanced situational awareness of spring wildfires in Alberta also have potential application by other agencies across Canada.

1.2 Data

The Alberta Wildfire Management Branch compiles in near real-time detailed information on wildfires in a system called FIRES (Fire Information and Resource Environment System). Data entry in FIRES began in 1990. FIRES is not a spatial system. It was developed to allow users to build reports and export data for use in other applications. Another system called AWARE (Alberta Wildfire Anticipation and Response Engine) is used to build Fire Weather Index (FWI) and Fire Behaviour Prediction (FBP) spatial outputs (i.e. maps). Unfortunately, AWARE is an operational system used in the current year and unable to be used to re-build historical maps.

Historical weather and Fire Weather Index System components, spatial wildfire data (i.e. wildfire perimeters for GIS use), and non-spatial wildfire data (non-spatial) are available on the Wildfire Alberta website (https://wildfire.alberta.ca/resources/historical-data/default.aspx). The historical wildfire perimeter data are available as ESRI Shapefiles (Geographic Coordinate System with a NAD83 datum) from 1931 to 2020 (last update year). Perimeters are only available from 1931 to 1997 for wildfires greater than or equal to 200 ha in size. After 1997, most wildfires greater than or equal to 12 ha in size are included in the data set.

From 1931 to 2001 “year” refers to the January 1 – December 31 period (12 months). From 2002 to 2017 “year” refers to the April 1 – March 31 period which is the government fiscal period. In 2018 “year” refers to the April 1 – December 31 period. In 2019 the period for “year” changed back to January 1 to December 31.

Changes to wildfire reporting procedures also occurred. In 2004, XA (small abandoned campfires) and OTR (order to remove) wildfires were entered into FIRES. An XA wildfire is defined as an abandoned campfire which takes less than fifteen minutes to extinguish. A wildfire is considered as XA if it is located anywhere except in an approved facility (e.g. fire ring, stove) inside a campsite engineered as a campground. Wildfire management staff completed a separate XA form for these wildfires. XA wildfires did not get entered into FIRES unless they exceeded a size threshold (which is related to the 15 minutes to extinguish them). It is not possible to extract XA wildfires from the FIRES system. OTR wildfires are "Order to Remove" wildfires, often trash and vegetation being burned in a barrel or in a small pile. The reporting of XA and OTR wildfires resulted in a spike in wildfire occurrences beginning in 2005.

Several fire history data sets are available from the Natural Resources Canada Canadian Wildland Fire Information System Datamart (Natural Resources Canada 2018). We used the National Fire Database fire point data to compile national wildfire statistics.

Deterministic atmospheric outputs from the ECMWF (European Centre for Medium-Range Weather Forecasts 2020) ERA5 reanalysis dataset (version 5) produced by Copernicus Climate Change Service at ECMWF were used to calculate Fire Weather Index codes and indices. ECMWF is an independent intergovernmental organization based in Reading, UK. ERA5 integrates large amounts of historical observations (satellite, in-situ and snow data) and uses advance modelling and assimilation systems to resolve a suite of hourly atmospheric, land surface and sea parameters. ERA5 land hourly data from 1981 to present are available from the C3S Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview).

1.3 Climate Change and Fire

The amount of moisture the atmosphere can hold is highly sensitive to temperature. As the temperature increases the capacity for a volume of air to hold water vapour also increases at the Clausius-Clapeyron rate (approximately 7% $°C^{-1}$). If the water vapour content for a volume of air remains the same, the relative humidity will decrease if the temperature increases. A warmer atmosphere therefore requires more moisture to reach saturation because the rate of vapourization increases and the saturation (maximum) vapour pressure increases. This means the atmosphere can draw more moisture from vegetation.

Increasing leaf temperature increases plant transpiration. Urban et al. (2017) found that a 10º C increase in temperature resulted in a 40% increase in stomatal conductance in both deciduous and coniferous trees. A warming atmosphere therefore dries not only dead and downed fuels but also live fuels. The increased evaporation of moisture from the forest floor, and vegetation increases the amount of fuel for burning. To compensate for every degree of warming and subsequent drying of fuels, precipitation has to increase by more than 15% for FFMC (Fine Fuel Moisture Code), about 10% for DMC (Duff Moisture Code), and about 5% for DC (Drought Code) (Flannigan et al. 2016). The FFMC, DMC, and DC are components of the Canadian Forest Fire Weather Index System (Van Wagner 1987) that provide relative measures of the moisture content of fine fuels (surface), upper duff, and deep organic layers respectively.

Increasing concentrations of carbon dioxide in the atmosphere will result in more plant growth (Idso et al. 1987) which increases the demand for water. This plant response is projected to reduce freshwater availability (used to fight wildfires) and soil moisture (Mankin et al. 2019). Climate change is resulting in extended wildfire seasons and increased severity of heatwaves. From 1936 to 2006, trembling aspen (*Populous tremuloides* Michx.) in the central parklands of Alberta has advanced its blooming by two weeks (Beaubien and Hamann 2011). Albert-Green et al. (2013) evaluated the seasonality of lightning-caused wildfires from 1961 to 2003 in Alberta and Ontario, Canada as a proxy for wildfire season length. Their results suggested that the wildfire season in Alberta is starting significantly earlier and finishing later. In their analysis of the seasonal distribution of wildfires Coogan et al. (2019) found an increasing trend in the number of lightning-caused wildfires ≥ 2 ha in size and lightning ignitions from 1981 to 2018. Jain et al. (2017) investigated the occurrence of trends in wildfire season length and extreme fire weather in North America from 1979 to 2015. The largest trend sizes and trends with the largest statistical significance were mainly positive indicating that climate change is extending the wildfire season and increasing the fire weather severity. In the western United States spring timing changes (i.e. early or late snowmelt) account for the frequency of large wildfires (Westerling 2016).

More and drier fuels support the growth of larger and more intense wildfires which increasingly limits the effectiveness of suppression efforts to manage these wildfires (Wotton et al. 2017). The increased fire weather severity (de Groot et al. 2013; Wang et al. 2015) will result in increased area burned (Flannigan et al. 2005; Tymstra et al. 2007; Hanes et al 2019). Wildfire management agencies across Canada will also be confronted with both more lightning and lightning-caused wildfires. Since 1975, lightning-caused wildfires have increased 2 – 5% each year in the boreal forest (Veraverbeke et al. 2017). In the United States lightning strikes are projected to increase due to global warming (Romps et al. 2014).

As noted by Podur and Wotton (2010), climate change will result in more frequent stress on wildfire management agency capacity. The province of Alberta will in particular be challenged because of the high level of industrial activity, and subsequent diverse and many values-at-risk requiring protection (Johnston and Flannigan 2018). Tymstra et al (2019a) suggest a paradigm shift in wildfire management is required which recognizes the positive and negative impacts of wildfire and the limits of suppression capability. This shift in managing wildfires includes i) strengthening and adjusting wildfire management capacity and capability to support a risk-based appropriate response approach to managing wildfires, ii) enhancing values protection (i.e. FireSmart), and iii) allowing for more managed wildfire on the landscape.

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2. Wildfire management in Canada: Review, challenges and opportunities

Cordy Tymstra, Brian J. Stocks, Xinli Cai, Mike D. Flannigan

2.1 Abstract

Wildfire management agencies in Canada are at a tipping point. Presuppression and suppression costs are increasing but program budgets are not. Climate change impacts and increasing interface values-at-risk are challenging suppression effectiveness and resulting in more wildfire disasters. We conducted semi-structured interviews with these agencies to understand the strategies, policies, and preparedness procedures they currently use to manage wildfires. We summarize the results of this national agency assessment, and based on what we heard and our review of agency internal documents, discuss agency challenges and opportunities to be better prepared for a future with more wildfire. A double fire paradox exists requiring communities and critical values in wildfire-dependent ecosystems to be FireSmart, and wildfire management agencies to allow more wildfire on the landscape by implementing a risk-based appropriate response approach. We conclude with a proposed future path for wildfire management in Canada. To coexist with wildfire, agencies in Canada must also strengthen and adjust their wildfire management capacity and capability. This necessitates stronger horizontal collaboration, enhanced resource sharing, and investments to develop innovative decision support tools, and an increased focus on prevention and mitigation.

2.2 Introduction

Wildfire is an important ecological process contributing to forest ecosystem health in Canada (Weber and Stocks 1998). On average from 1970 to 2017, 8,000 wildfires occurred and burned 2.25 million ha across Canada annually (1970 – 2016 period: Canadian Forest Service 2017; 2017 year: Canadian Interagency Forest Fire Centre 2017) (Fig. 2.1). The area burned is highly variable ranging from 289,000 ha in 1978 to 7.56 million ha in 1989. Over the last several decades the frequency of large wildfires in Canada have increased (Hanes et al. 2019). Lightning, human activity and unknown causes account for 47 %, 49 %, and 4 % respectively of all wildfires (1990 – 2016).

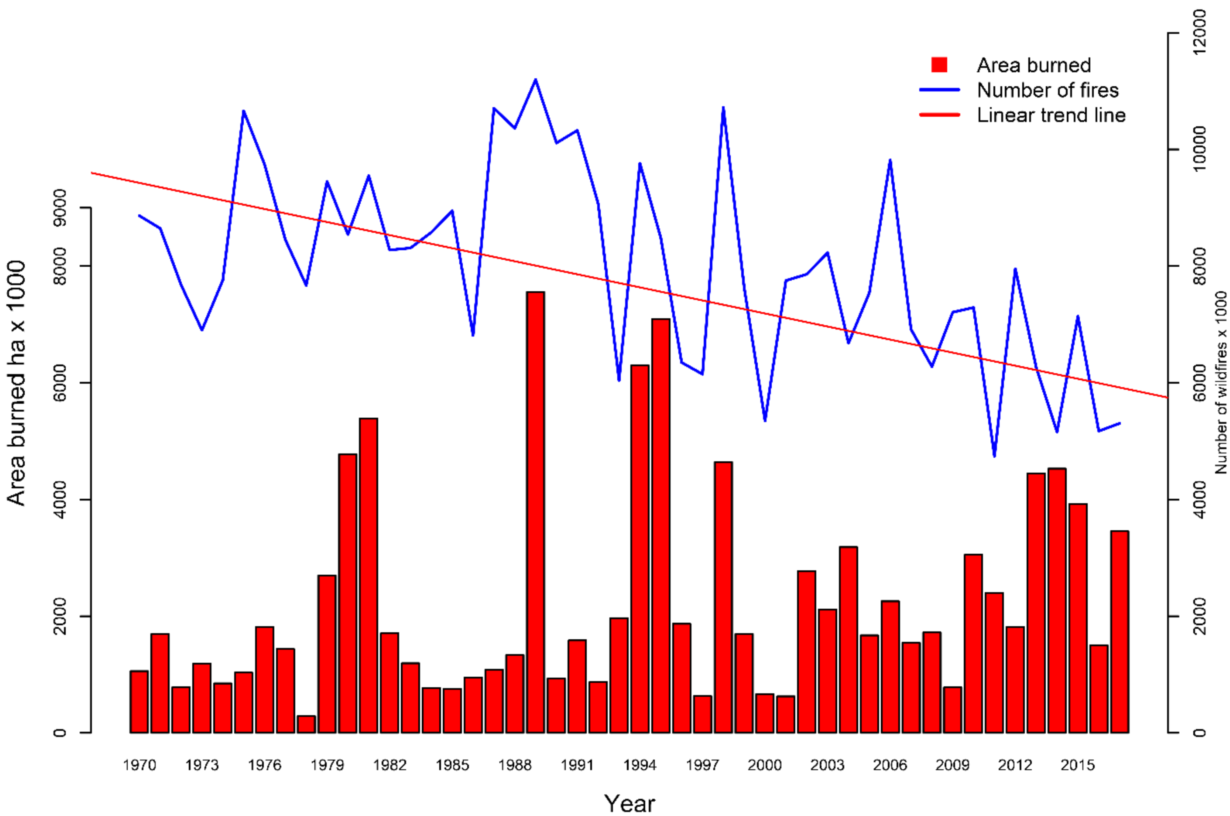

Figure 2.1 Number of wildfires and area burned in Canada 1970 – 2017. The red line is a linear trend of the number of wildfires. The blue line is the annual number of wildfires.

Few wildfires are disasters; the majority are managed and result in no or few negative impacts. However, when wildfire disasters occur the impacts can be significant. The costliest Canadian wildfire disasters based on incurred insurance claims adjusted for inflation (2017 $), include the 2003 Kelowna wildfires in British Columbia ($252 million), 2011 Slave Lake wildfires in Alberta ($864.67 million), the 2016 Horse River Wildfire in northeastern Alberta ($3.84 billion: costliest natural disaster in Canadian history), and the 2017 wildfires in British Columbia ($137.3 million) (A. Bartucci, Insurance Bureau of Canada, Personal Communication, October 10, 2017). The total cost of wildfire disasters are considerably higher when suppression costs, recovery costs, lost revenue, and other impacts (e.g. air and water quality) are also accounted for (Butry et al. 2001, Headwaters Economics 2018).

Wildfire risk management incorporates the four integrated phases of emergency management: prevention and mitigation, preparedness, response and recovery (Public Safety Canada 2017). Although mitigation can be part of preparedness, we consider them as two separate phases; prevention focusing on preventing wildfires, and mitigation aiming to reduce the impacts when they do occur. Wildfire preparedness is those actions that contribute to a state of readiness to adequately manage wildfire arrivals and their possible consequences. The actions taken to manage a wildfire incident when they do occur are referred to as response. The recovery phase includes all efforts to repair or rebuild conditions during and after a wildfire disaster.

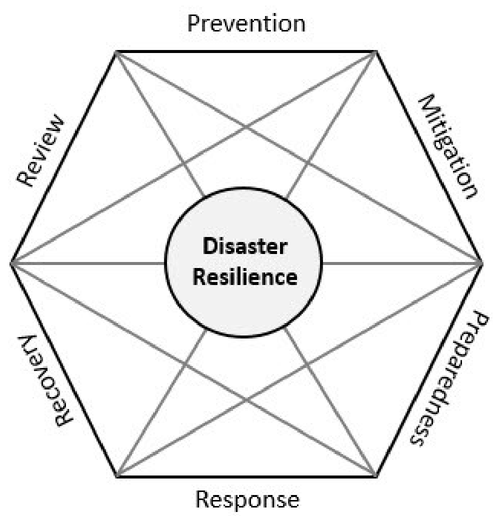

Figure 2.2 Wildfire management phases

We also include "review" as a separate phase of wildfire management (Fig. 2.2). Many of the changes and advancements in wildfire management in Canada occurred as a result of the implementation of recommendations from post-wildfire disaster debriefing sessions, and internal and independent reviews. Notable recent independent wildfire reviews in Canada include the Firestorm 2003 Provincial Review in British Columbia (Firestorm 2003 Provincial Review Team 2004), 2011 Flat Top Complex Wildfire Review in Alberta (Flat Top Complex Wildfire Review Committee 2012), Lessons learned report of the Lesser Slave Lake Regional Urban Interface

Wildfire (KPMG 2012), Review of Alberta's Wildfire Management Program and 2015 Fire Season (MNP 2016), 2016 Horse River wildfire reviews in Alberta (KPMG 2017; MNP 2017), and the review and findings of the 2017 British Columbia flood and wildfire review (Abbott and Chapman 2018).

McGee et al. (2015) provide an overview of wildfire in Canada but their review does not include operational wildfire management. Our wildfire management review includes strategy and policy (priorities), roles and responsibilities, prevention regulatory tools, and how federal, territorial and provincial wildfire management agencies in Canada, hereafter referred to as agencies, prepare for managing wildfires. We define strategy as the approach taken to achieve a goal, whereas policy is decision oriented, subordinate to strategy, and implemented as operating procedures and business rules.

The objective of our review is to document the current state of wildfire management in Canada, and discuss the challenges and opportunities of agencies to address a future landscape with more wildfire. Our approach included fire occurrence data analysis, literature review with an emphasis on internal agency reports not available on-line, and supplementary interviews to fill information gaps and identify agency challenges. The terms "fire", "forest fire", "wildland fire" and "wildfire" are used across Canada, and often interchangeably. In this paper we use the term wildfire, which is commonly used in North America to refer to all unwanted lightning and human-caused fire in all vegetated land cover types.

We first describe the roles and responsibilities of wildfire management in Canada. This is followed by an overview of wildfire management strategy. The next section focuses on the wildfire prevention regulatory tools used by agencies across Canada. Wildfire preparedness at the national and agency levels is described in the following two sections. In the wildfire management and opportunities section we introduce a wildfire management paradigm shift triangle. In the last section we propose a path forward to facilitate the implementation of this transformational pivot.

Twelve semi-structured interviews that engaged a total of 19 people were conducted from December 2017 to April 2018 with staff from the Canadian Interagency Forest Fire Centre (CIFFC) member agencies. This qualitative exploratory method used five open thematic questions (Table 2.1), and if required additional sub-questions to prompt discussion and further explore the responses given. We purposively sampled the CIFFC Fire Science Committee agency representatives, and later recruited alternate and/or additional interviewees (n = 26) based on recommendations from our initial contacts. CIFFC is a private, non-profit corporation providing wildfire management services to its member agencies (10 Provinces, 2 Territories, and 2 Federal) to improve wildfire management in Canada.

Table 2.1 Semi-structured agency interview questions

Question 1: What is the organizational structure and role of your agency? Premise: Future landscapes with more frequent intense wildfires necessitate greater collaboration between emergency management organizations at all levels of government. Organizational structure, roles and responsibilities influence collaborative opportunities.
Question 2: What wildfire management strategy does your agency follow? Premise: Some wildfire management agencies are transitioning from a zone response approach to a wildfire by wildfire appropriate response approach.
Question 3: How does your agency determine its preparedness level? Premise: Most preparedness systems are based on rapid and aggressive initial attack to prevent large escaped wildfires that are costly and difficult to contain.
Question 4: Does your agency issue fire weather and fire behavior advisories and/or warnings? Premise: Advisories and warnings can provide enhanced situational awareness for wildfire management staff as well as stakeholders.
Question 5: What regulatory tools does your agency use to prevent wildfires? Premise: Approximately 50 % of wildfires in Canada are human-caused. Reducing human-caused wildfires can reduce costs and impacts.

We additionally obtained GIS data layers from the agencies of their wildfire management areas and response zones. Prince Edward Island was not included in our interviews because their forest protection program is small, and no data are available in the Canadian National Fire Database due to a legacy wildfire size threshold of 200 ha. The Territory of Nunavut was also excluded because it is covered predominantly by Arctic tundra, and wildfires are thus rare.

Wildfire occurrence and burned area data for full and modified response wildfires for the 1997 – 2017 period were obtained from the CIFFC annual Canada Reports as reported by CIFFC's member agencies (Canadian Interagency Forest Fire Centre 2017). To evaluate wildfire cause and trends for a longer period (1970 – 2017) we used data from the Canadian National Fire Database (Canadian Forest Service 2017) for the 1970 – 2016 period, and the CIFFC annual Canada Reports for 2017.

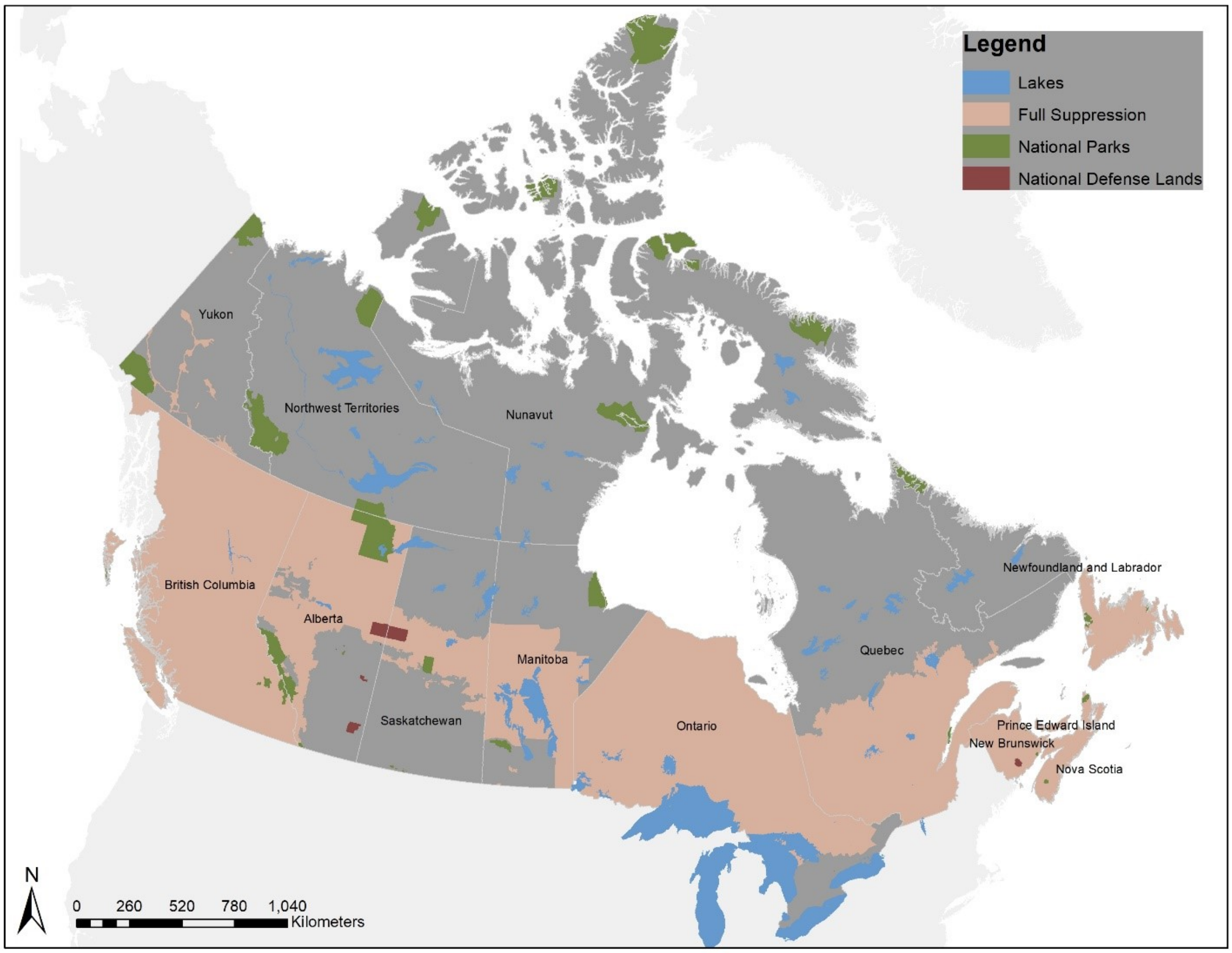

Figure 2.3 Provinces, territories, national parks (western, central and northern), national defense lands, and the full suppression wildfire management area in Canada

2.2 Wildfire management roles and responsibilities

Canada is a confederation with a constitutionally recognized federal government and ten provinces (British Columbia [BC], Alberta [AB], Saskatchewan [SK], Manitoba [MB], Ontario

[ON], Quebec [QC], Newfoundland and Labrador [NL], New Brunswick [NB], Nova Scotia [NS], and Prince Edward Island [PE]); and three territories (Yukon Territory [YT], Northwest Territories [NT] and Nunavut Territory [NU]) with governing powers entrusted by the Parliament of Canada (Fig. 2.3). To facilitate the effective management of all emergencies, governments in Canada have adopted an all-hazard approach to manage natural and human-caused hazards and disasters (Public Safety Canada 2017). Established in 2003, Public Safety Canada provides national coordination across federal agencies to implement the all-hazard approach for emergency management on federal lands and properties in Canada.

About 6% of the forest lands in Canada is privately owned; management of the remaining 94% is the responsibility of the provinces and territories (90%), and federal institutions (4%) (national parks, First Nations reserves, and the Department of National Defense lands) (Government of Canada 2018). Although the provincial and territorial governments are responsible for wildfire management on the lands they own, not all of their forested areas are actively managed (Fig. 2.3).

Only nine percent (9.2%) of the reported wildfires in Canada are categorized as modified response but they account for 64% (63.7%) of the total area burned for the period 1997 – 2016 (Canadian Interagency Forest Fire Centre 2017). Modified response wildfires in SK and NT alone contribute 50% of the total area burned in Canada by modified response wildfires. An estimated 80% of these wildfires are lightning caused (Canadian Forest Service 2017) and occur in the northern zones where there are fewer people and industrial activities.

Wildfire management agencies in Canada have evolved, and essentially remained as stand-alone, single-hazard wildfire control organizations. There are a few exceptions. The YT Wildland Fire Management Branch, and the YT Emergency Management Organization, are organizationally within the same ministry, and Ontario's Aviation, Forest Fire and Emergency Services Branch protects people, property and communities from multiple natural hazards (emergency response to fire, flood and soil erosion). In 2019, the SK Wildfire Management Branch, and the Emergency Management and Fire Safety organization became part of the Saskatchewan Public Safety Agency (Government of Saskatchewan 2019).

Emergency management at the national level is the responsibility of the federal government within its areas of exclusive jurisdictions, and on land and other assets it controls. About 10% of emergencies in Canada require engagement and assistance from the federal government when a province or territory is unable to manage an emergency. When an emergency has national consequences, the federal government may, with legislative authority, intervene or share the management responsibility. The federal government has agreements with the provinces and territories respecting the management of wildfires on federal lands. Indigenous Services Canada, and provincial and territorial wildfire management agencies have fire control agreements to ensure Indigenous communities on Federal Reserves are prepared and able to respond to the threat of wildfire. Similar agreements are made with National Defense and the provinces and territories to manage wildfires on federal lands owned by national defense. The provinces and territories also have agreements with Parks Canada to address the shared management of wildfires along national park borders.

When a wildfire threatens a community or critical values-at-risk, the local emergency management organization responds to manage the situation. If the incident cannot be managed by the local responders, the provincial or territorial emergency management organization is activated to help coordinate the government's wildfire emergency response and recovery. A Provincial or Territorial State of Emergency typically triggers a provincial request for federal assistance. This results in Public Safety Canada's activation of their Government Operations Centre (GOC) to monitor and share situational awareness information, and coordinate the federal response across its various Departments to the provincial request for assistance.

2.3 Wildfire management strategy

The approach to managing wildfires in Canada is based on either zonation or no zonation, and full response or risk-based appropriate response (Table 2.2). The adoption of a risk-based appropriate response approach is a result of disastrous wildfire seasons and subsequent reviews and policy change recommendations, recognition of the ecological role of wildfire, and the need to control costs. Decisions are made on a wildfire-by-wildfire basis regarding the commensurate wildfire management effort required to follow policy and attain desired objectives. This includes

Table 2.2 Federal, territorial and provincial areas of responsibility, fire season length, and wildfire management strategy and policy (FPT = federal, provincial, territorial, YT = Yukon Territory, BC = British Columbia, AB = Alberta, NT = Northwest Territories, SK = Saskatchewan, MB = Manitoba, ON = Ontario, QC = Quebec, NL = Newfoundland and Labrador, NB = New Brunswick, NS = Nova Scotia, PI = Prince Edward Island, PC = Parks Canada National Parks)

FPT	Mandated Area of Responsibility/ Length of Fire Season	Policy (Response Priorities)	Strategy (Approach)
YT	All territorial lands outside Whitehorse city limits; federal lands excluded. Fire season: April 1 – September 30	1. Life 2. Property 3. Communities	Protect life, property, and communities while also maintaining the ecological role of fire. The appropriate response is based on zonation: 1. Critical Fire Management Zone 2. Full Fire Management Zone 3. Strategic Fire Management Zone 4. Transitional Fire Management Zone 5. Wilderness Fire Management Zone
BC	All crown land; other public and federal lands through Fire Control Agreements. No official fire season.	1. Human life and safety 2. Other protection priorities include: 2.1 communities, infrastructure, other assets; 2.2 mitigation of impacts on key environmental values, and; 2.3 maintenance of other natural resource values through the use of prescribed wildfires.	Respond to all wildfires but consider monitoring and managing those wildfires of minimal risk to communities, infrastructure or resource values. Deliver cost-effective proactive wildland fire management. Zonation: None
AB	Legislated Forest Protection Area; other public and federal lands through Fire Control Agreements. Wildfire suppression provided on federal lands through agreements. Fire season: March 1 – October 31	1. Human life 2. Communities 3. Sensitive watersheds and soils 4. Natural resources 5. Infrastructure (with major impact on public safety or the local and provincial economy)	Initial attack all wildfires before they exceed 2 ha in size but if unsuccessful, use an appropriate response approach guided by a wildfire analysis strategy or approved wildfire management plan. Zonation: None other than as identified in approved wildfire management plans.
NT	All territorial lands including settled land claim areas. Fire season: May 1 – September 30	1. Life 2. Property (communities and other infrastructure) 3. Natural resource values 4. Cultural resource values Priorities other than life are based on relative value of resources and assets relative to the cost of continuing sustained attack on wildfire occurrences.	Appropriate response: Every wildfire requires a decision on the magnitude and type of response. High priority areas include communities, high value commercial forests, and recreational assets. During extreme weather conditions suppression is likely ineffective but wildfire is recognized as an important ecological process. Zonation: None.
SK	Provincial crown forest (35.5 million ha); other public and federal lands through Fire Control Agreements. Fire season: April 1 – October 31	1. Human life 2. Communities 3. Commercial forests 4. Major public infrastructure	Values-at-risk approach ensuring human life and safety are the highest priority while allowing the ecological role of wildfire to occur, and reducing the probability of extreme cost events. Zonation:

			1. Community Full Response Zone 2. High value Commercial Forest Full Response Zone 3. Modified Response Zone 4. Observation Zone (Monitored Response)
MB	Legislated Primary Protection Zone and Burning Permit Area; protection provided outside the Protection Zone when requested or deemed necessary (values at risk) and resources are available. Suppression may occur on other public and federal lands through Fire Control Agreements. Fire season: April 1 – November 15	1. Human life 2. Significant property, forest and other resource values	Appropriate response based on assessments of each wildfire and zonation: 1. Primary Protection Zone (Full Response) 1.1 Low Priority 1.2 Medium Priority 1.3 High Priority 2. Northern Observation Zone (Monitored Response but protect communities and important infrastructures) 3. Agricultural Zone (Response based on requested assistance)
ON	All crown land including unincorporated Townships; other public and federal lands through Fire Control Agreements. Fire season: April 1 – October 31	1. Human life and safety 2. Property losses 3. Economic and societal disruptions	Appropriate response: Each wildfire is assessed and an appropriate response made based on the situation. This approach supports the ecological role of fire, and use of fire to attain resource management objectives. Zonation: None
QC	Forested land area as defined by the Minister; other public and federal lands through Fire Control Agreements. Fire season: April 1 – November 15	1. Human life 2. Public and private infrastructure critical to public safety 3. Likelihood of attaining operational objectives 4. Forest resource value	Wildfire management is the responsibility of the Ministry of Forests, Wildlife and Parks; the Minister may certify a non-profit organization (currently SOPFEU) to provide forest fire protection in Quebec. SOPFEU's objective is to provide quality forest fire protection services with rigorous cost control. Zonation: 1. Intensive Zone (Full Response) 2. Northern Zone (Modified and Monitored Responses but protect infrastructures and communities)
NL	All crown lands. Fire season (Island): May 1 – September 30 Fire season (Labrador): May 15 – September 30	No formal list of priorities; wildfires are prioritized based on values-at-risk.	Newfoundland: Full response Zonation: Labrador: Full Response and Monitored response zones.
NB	All crown lands. Fire season: 3rd Monday April – October 31	No formal list of priorities; wildfires are prioritized based on values-at-risk.	Full response for the entire Province. Zonation: None
NS	All crown lands. Fire season: March 15 – October 15	No formal list of priorities; wildfires are prioritized based on values-at-risk.	Full response for the entire Province. Zonation: None
PI	All crown lands.	No formal list of priorities; wildfires are prioritized based on values-at-risk.	Full response for the entire Province.

	Fire season: March 15 – November 30		
PC	All National Park and Historic Park lands. Fire season: Varied	No formal list of priorities; wildfires are prioritized based on values-at-risk.	Zonation: 1. Intensive Zone (Full Response) 2. Intermediate Zone (Appropriate Response) 3. Extensive Zone (Modified and Monitored Response)

the decision whether or not to initial attack a wildfire. Risk-based appropriate response allows for the use of multiple responses (full, modified or monitored) over time and space to concurrently manage multiple objectives including the allowance of wildfire as a natural ecosystem process. There is considerable variation across Canada in the level of analysis used to support risk-based appropriate response decisions and hence the ability to apply a defendable and repeatable process.

Full response refers to the fast and aggressive initial attack and/or sustained action on a wildfire until it is under control. A modified response refers to the use of a suite of suppression tactics to manage and contain a wildfire within a maximum allowable perimeter. Containment perimeters are determined by analyzing the wildfire environment (fuel, weather and topography) and wildfire behavior potential, and then identifying the opportunities to contain the wildfire. This analysis can be pre-planned (O'Connor et al. 2016) or completed as part of the response.

Monitored response wildfires are observed and assessed to determine whether suppression action should be taken or not (Canadian Interagency Forest Fire Centre 2021a). Modified and monitored responses both allow for the attainment of land and resource management objectives while minimizing costs and impacts to values-at-risk, but monitored response wildfires do not have a perimeter containment objective.

Agencies using a full response approach implement risk-based appropriate response by default when a wildfire load surge occurs. Wildfires are prioritized based on a risk assessment and appropriate responses made depending on the availability of resources. Regardless of zonation and response approach, the protection of human life and communities is the first priority of all wildfire management agencies. The suppression priority of other values at risk across Canada vary by agency (Table 2.2).

We include wildfire management zone maps for each agency as supplementary material to illustrate the various types of zonation used across Canada (Appendix B Fig. A1-A13). The Parks Canada Agency is responsible for managing wildfires within the national parks. Individual zone maps for each national park were excluded to limit the size of the supplementary material.

2.4. Wildfire preparedness – national level

The federal Department of Natural Resources (NRCan) monitors wildfire danger conditions to provide situational awareness at the national level to support CIFFC and the federal government's public safety mandate. This information is published in the Canadian Wildland Fire Information System (CWFIS) as Canada-wide map products based on the Canadian Forest Fire Danger Rating System (CFFDRS). The CWFIS includes various outputs of fire weather, fire behavior, active burning fires, fire weather normals, and monthly and seasonal forecasts.

CFFDRS provides the foundation for understanding the fire environment and obtaining early warning of potential wildfire events (Stocks et al. 1989; Taylor and Alexander 2006; de Groot et al. 2015). First released in 1969, the Fire Weather Index (FWI) sub-system of CFFDRS, calculates three standard fuel moisture codes and three fire behaviour indices to generally characterize fire danger conditions across Canada. An interim version of the Fire Behaviour Prediction (FBP) Sub-system was released in 1984. The full version of the FBP System was released in 1992 (Forestry Canada 1992). This sub-system provides quantitative estimates of fire behavior (e.g. fire intensity, rate of spread, fuel consumption) for 16 fuel types. The development of a national Fire Occurrence Prediction (FOP) sub-system, and enhancements to the existing FWI and FBP sub-systems are on-going.

Early situational awareness is an important component of wildfire preparedness. It begins with the perception of elements in the environment over time and space, followed by the interpretation and full understanding of their meaning, and ends with the forecast of their condition into the future (Endsley 1995). Each day, agencies determine the required resources to cope with forecasted wildfire conditions based on various outputs from CFFDRS subsystems including Fire Weather Index (FWI), Fire Behavior Prediction (FBP) and Fire Occurrence

Prediction. The determined readiness is reported as an agency preparedness level (APL) to CIFFC (Table 2.3). Six situational awareness elements are rated for each of the five preparedness levels. CIFFC assesses the daily agency APLs and the level of resource demand and availability in Canada, and using a decision criteria tree (Canadian Interagency Forest Fire Centre 2021b), makes a determination of a daily national preparedness level (NPL) (Table 2.4) for inclusion in their National Wildland Fire Situation Report.

Table 2.3 Agency preparedness level and typical rating for associated criteria included in the CIFFC National Wildland Fire Situation Report

Criteria	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Agency fire hazard	Low	Low – Mod	Mod – High	High – Extreme	Extreme
Current fire load	Low	Low – Mod	Mod – High	High	High - Extreme
Anticipated load (7 days)	Low	Moderate	High	High – Heavy	Heavy
Agency resource level	Adequate	Adequate	Some Assistance	Assistance Required	Inadequate
CIFFC request for mutual aid response level	Excellent	Good	Mod – Poor	Poor – Nil	Nil
Potential for international assistance	Nil	Nil	Nil	Increasing	Consideration

Table 2.4 National preparedness level and associated criteria rating used by CIFFC to determine a National Preparedness Level

	Level 1	Level 2	Level 3	Level 4	Level 5
Significant wildland fire activity	Little or none	Increasing in a few agencies	One or more agencies with Incident Management Teams engaged	Two or more agencies with Incident Management Teams engaged	Two or more agencies with Incident Management Teams engaged
Resource demand and mobilization	Low	Low - Moderate	Moderate - High	High	Extreme
Potential for emerging significant wildland fires	Minimal	Normal	Normal	High – Extreme	High - Extreme

Agencies across Canada maintain a level of resource availability (capacity) to adequately manage most wildfire load conditions. Wildfire load is described as the number and magnitude (size and head fire intensity kW/m) of wildfires (Canadian Interagency Forest Fire Centre 2021a). Martell (2001) extended the concept of wildfire load described by Turner (1973) as the size of the wildfire management effort associated with wildfires within a specific spatial and temporal domain. The Incident Command System Incident Types (1 to 5) (Canadian Interagency Forest Fire Centre 2021a) provide a relative measure of wildfire management effort but agencies do not report incident type to CIFFC.

CIFFC manages a unique intra-Canadian agreement called Mutual Aid Resources Sharing (MARS) to facilitate the cost effective sharing of firefighting resources when agencies need additional resources for preparedness and/or response. Canada also has four regional reciprocal forest fire fighting arrangements with the United States called compacts. These regional protection agreements do not supplant existing national agreements (MARS agreement and the Canada/United States Reciprocal Forest Fire Fighting Arrangement). Only provincial, territorial and state resources are mobilized through the compact. The exchange of resources across Canada occurs through CIFFC, not the compacts.

The collective pool of available agency resources through CIFFC is not always able to meet the national demand due to increasing resource shortages (Tsang et al. 2013). CIFFC therefore has an agreement with the United States, and arrangements with Mexico, Australia, New Zealand and South Africa to allow for the efficient exchange of resources from other countries.

In 2016, CIFFC strengthened its strategic planning services through the activation of a new Strategic Planning Unit to provide forward planning, timely intelligence, and linkage with federal agencies and international partners. A new Canadian Multi-Agency Coordination (CMAC) Group was also established to assist in setting national priorities, anticipate future resource demand, and assist in resolving any issues (Canadian Council of Forest Ministers Wildland Fire Management Working Group 2016b). The Strategic Planning Unit and the CMAC Group are activated when the national preparedness level (NPL) reaches 3 or higher (on a scale of 1-5). A national 10 to 14 day situation outlook of wildfire activity and agency resource demand is under development to support the Strategic Planning Unit. This outlook will provide critical preparedness intelligence to support decisions to mobilize resources in advance. It takes 3 – 5 days to mobilize resources across Canada and 10 – 14 days to import resources outside of Canada.

2.5. Wildfire prevention regulatory tools – wildfire management agency level

Agencies are given authority to prevent and manage human-caused wildfires through various acts and regulations, policies, and operating procedures. The strategic use of regulatory tools to reduce the number of human-caused wildfires is typically included in preparedness escalation protocols. Regulatory tools allow agencies to issue fire permits and permit conditions; fire advisories, restrictions, and/or bans; forest area closures; and operation of equipment and/or off highway vehicle restrictions. Fire control agreements with industry, municipalities and federal agencies also include conditions to help prevent wildfires.

Agencies identified forest area closure as a very effective tool, but cautioned they can impact travel and tourism which contributed $127.3 billion to Canada's GDP in 2016 (World Travel and Tourism Council 2017). Area closures therefore need to be declared and removed strategically and quickly to minimize disruption. The Atlantic Provinces consider forest area closures as too restrictive and usually apply other regulatory tools. Fire permits were identified by all agencies as the preferred regulatory tool because face-to-face communication can be made when they are issued in person and specific conditions can be included on the permits based on site inspections. Saskatchewan and British Columbia use on-line systems to track permitted fires to ensure resources are only dispatched to wildfires requiring control.

Agencies identified fire bans as the second most preferred regulatory tool to prevent wildfires. We found that agencies have considerable flexibility in the use of various fire bans. For example, on July 19, 2017 a fire restriction was issued in the Forest Protection Area (FPA) in southwest Alberta along the mountains and foothills south of the Red Deer River to Highway 532. Existing fire permits were suspended and no new fire permits issued. Campfires were only allowed in campgrounds with engineered fire pits with rings in place. The use of fireworks and exploding targets were also prohibited. Eight days later (July 27th), a fire ban issued in the Forest Protection Area from the Red Deer River south to the north boundary of Waterton Lakes National Park, prohibited all outdoor fires, including fires within campgrounds. A forest area closure then came into effect on September 4th. The fire ban and forest area closure continued until September 13th but a restriction on the use of off-highway vehicles remained in effect for another two weeks.

Examples of other regulatory tools to prepare for forecasted seasonal and year-to-year wildfire conditions and trends, include the authority to, if required, change the start and end of the wildfire season, and the amounts for cost recovery, and penalties for violations of agency acts and regulations.

2.6 Wildfire preparedness – wildfire management agency level

We found considerable differences in how CIFFC member agencies determine their APL, and the level of decision support (tools) used to make these determinations. For example, although all agencies use the FWI System, they do not all use the same number of FWI classes and class breakpoints. Various decision support models and systems based on the CFFDRS such as the Canadian Wildland Fire Information System (Carr et al. 2016), Spatial Fire Management System (Lee et al. 2002), Prometheus (Tymstra et al. 2010), FWI.FBP R Package (Wang et al. 2016), Burn-P3 (Parisien et al. 2012), REDapp (REDapp Community 2019), and FOP models (Taylor et al. 2013) are available but not used consistently across Canada. Most agencies in Canada have also developed their own proprietary systems similar to the CWFIS to provide wildfire danger situational awareness.

Agencies prepare for tomorrow by understanding the wildfire behavior growth potential of today's wildfires (current load) and tomorrow's new wildfire arrivals (forecasted load), and their threat to values-at-risk. The appropriate type and number of resources are then readied and prepositioned to locations with the highest risk. This information is included in a preparedness plan completed each day for tomorrow's preparedness activities. Fire weather and fire behavior advisories and warnings provide important preparedness situational awareness but there is no national standard, and not all agencies use these decision aids consistently.

Suppression resources for initial attack and sustained attack (extended suppression activities once a wildfire escapes initial attack) are usually managed separately. Although most of the 173 wildfires reported by the British Columbia Forest Service on July 7, 2017, occurred in the Cariboo and Nicola-Thompson Regional Districts, resources elsewhere in the province were not available because of the high potential for new wildfire starts. New wildfire starts are a priority requiring committed initial attack resources. If however, the wildfire risk is low in one or more areas, most, or even all of the resources from these areas can be moved to other areas with very high to extreme wildfire risk.

Most agencies use escalation protocols to describe activities that are considered at each preparedness level. Alberta for example, considers activation of an Intelligence Unit when preparedness level 3 is reached. Escalation protocols identify when the import of resources should be considered. When a wildfire surge occurs, resource demand can quickly exceed resource availability. An agency's surge response capability can be strengthened by predicting when these surges are likely to occur; activating the appropriate preparedness level; and requesting additional resources from CIFFC in advance from other agencies across Canada or other countries. Escalation protocols are an important component of preparedness but during our interviews we learned that agencies differed widely in their application.

Agencies who use zones to delineate areas by response priority adjust their preparedness accordingly by zone. Zonation influences response type which in turn influences preparedness. Within response zones identified as modified or monitored, the wildfire management effort focuses on the protection of life, communities and critical infrastructure.

Despite the different preparedness approaches used by wildfire management across Canada, the level of readiness and associated budgets are all motivated by wildfire behavior potential and the values-at-risk deemed requiring protection. Johnston and Flannigan (2018) mapped 32.3 million ha of wildland-urban interface in Canada. They also mapped additional interface areas called the wildland-industrial interface (10.5 million ha) and the wildland-infrastructure interface (109.8 million ha). Regions with increasing wildfire activity and interface development will likely experience increasing interactions between wildfires and values-at-risk. Since 1980 the number of disasters by decade in Canada have increased (Fig. 2.4), with large numbers of evacuees occurring in 2016 and 2017.

Since preparedness determination is not consistent across Canada we provide an overview of preparedness for each agency as supplementary material. We highlight disastrous wildfire years and subsequent policy changes, and include selected examples of decision support tools used to support response and preparedness to illustrate the range of products used across Canada.

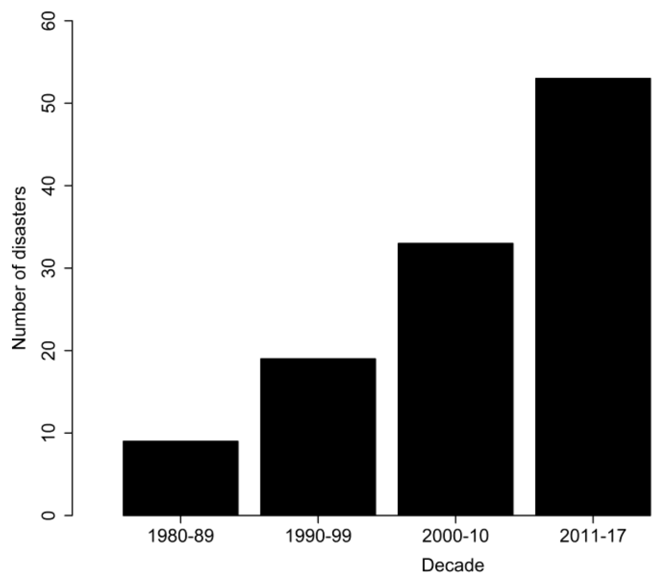

Figure 2.4 Number of wildfire disasters in Canada by decade (1980 – 2017). 1980 – 2016 data. 1980 – 2016 data: Canadian Disaster Database, (Public Safety Canada 2018); 2017 data: estimated from online open sources.

Agencies in Canada are quite successful at fighting wildfires. Only 4% of all wildfires exceed 200 ha in size but they are responsible for about 99% of the total area burned for the 1990 – 2016 period (Canadian Forest Service 2017). Projected increases in area burned suggest the current state of wildfire management in Canada will be unable to cope with a future landscapes with increasing wildfire activity. After the deadly 2009 "Black Saturday" bushfires in Australia, O'Neill and Handmer (2012) argued the need for transformative adaption in wildfire risk management to be better prepared. Transformational change is also required in Canada. In the next section we discuss agency challenges and opportunities to make this happen.

2.7 Wildfire management challenges and opportunities

Wildfire management agencies are unlike most emergency management organizations because they manage natural and anthropogenic wildfire with both negative and positive impacts (Moritz et al. 2014), and must decide which wildfires are keepers and which ones are not (Martell 2001), and when to fight wildfire with fire. The challenges of this decision-making process include species-at-risk management and competing land uses (Donovan et al. 2017; Skatter et al. 2017), non-market valuation (Venn and Calkin 2011), significant wildland-urban, -industrial, and -infrastructure interface developments (Johnston and Flannigan 2018), increasing wildfire disasters (Fig. 2.4), smoke management concerns (McLennan and Pankratz 2017), significant climate change impacts (Flannigan et al. 2009), increasing fixed (pre-suppression) and variable (suppression) costs and increasing variability of these costs (Stocks and Martell 2016). Increasing government accountability requires agencies to confront these challenges while also managing their budgets efficiently (Dallyn 2012).

The projected impacts of climate change include longer wildfire seasons (Wotton and Flannigan 1993; Albert-Green 2013; Woolford et al. 2014; Beaubien and Hamann 2011), increasing fire weather severity (de Groot et al. 2013; Wang et al. 2015; Flannigan et al. 2016), increasing wildfire occurrence (Wotton et al. 2003; Wotton et al. 2010), and increasing fire intensity and area burned (Flannigan et al. 2005; Tymstra et al. 2007; Balshi et al. 2008; Podur and Wotton 2010; Wotton et al. 2017). Under low and high climate change scenarios, suppression costs are projected to increase by 60% and 199% respectively (Hope et al. 2016).

The climate change impacts translate operationally to reduced suppression effectiveness because wildfire management agencies will experience more days when their suppression efforts at current levels are not capable of effectively managing escaped wildfires because of projected higher wildfire intensities (Wotton et al. 2017). Forest fuel composition, structure and load changes due to decades of wildfire suppression also contribute to the challenge of managing wildfires (Keane 2002; Hessburg et al. 2005). This is the fire paradox (Arno and Brown 1991) whereby the suppression of stand-maintaining wildfires promotes fuel buildup and continuity. In the boreal forest wildfire suppression has led to a reduced mosaic at the landscape level (Ward and Tithecott 1993; Ward et al. 2001; Martell and Sun 2008).

Wildfire suppression contributes to a wildfire problem but paradoxically it is wildfire use that will help to solve this problem (double fire paradox). The wildfire management toolbox must include wildfire use to manage wildfires at the landscape scale because it is not feasible to effectively use prescribed burns and/or fuel management treatments alone to restore expansive wildfire-dependent ecosystems (Amiro et al. 2001; Schoennagel et al. 2017).

A major barrier in Canada to address the double fire paradox is the inadequate funding to support the vision of an innovative and integrated approach to wildfire management. Mitigation funding has followed wildfire disasters but not at the same level to mitigate flood (Blais et al. 2016) and earthquake disasters (Vancouver Sun 2015). Despite the increasing occurrence of wildfire disasters in Canada, funding to support wildfire prevention, mitigation and preparedness have not kept pace with the increasing need to mitigate the impacts from wildfires, and be better prepared when they do arrive. This disparity in funding has left agencies with few options to confront the changing wildfire environment. They can reduce their performance targets and accept more losses, or reduce their primary protection areas and focus on protecting high priority values-at-risk. Unfortunately, these types of management adaptations and the increasing risk of major losses from wildfire are not well understood by the public or politicians.

To overcome the many challenges confronted by wildfire management agencies, we propose a paradigm shift to strengthen suppression capacity and capability, enhance values protection (FireSmart), and allow more managed wildfire on the landscape (Fig. 2.5). To accomplish this, agencies need to align their capacity and capability to use a risk-based appropriate response approach that supports both wildfire suppression and use.

Strategically allowing more managed wildfire on the landscape using a risk-based approach contributes to disaster risk reduction through a negative feedback. If wildfires and prescribed burns function as effective fuel treatments, they can have a regulatory effect on the occurrence of subsequent wildfires (Amiro et al. 2001; Parks et al. 2015). Wildfires can mitigate wildfire initiation (Parks et al. 2016,) and flammability (Héon et al. 2014), thereby regulating area burned.

Enabling more wanted wildfire in wildfire-dependent ecosystems using modified and monitored responses can be facilitated if containment opportunities (i.e. wildfire management planning) are pre-planned, wildfire risks to communities and other high values are reduced (FireSmart), and a repeatable, defendable decision making process is used. There is however, no consistent, risk assessment approach to guide appropriate response in Canada.

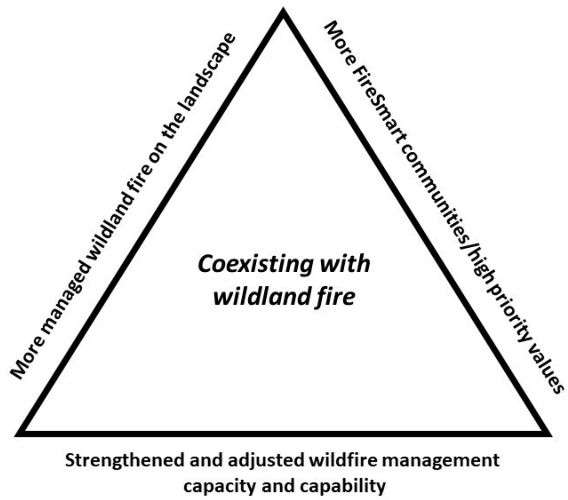

Figure 2.5 Coexisting with wildland fire triangle describing an integrated wildfire management approach (paradigm shift) to address a future landscape with more intense and severe wildland fires.

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During our interviews, most agencies identified cross-ministry linkages as another challenge. A disconnection with the ministries responsible for land and resource management creates barriers to integrate wildfire as an ecological process at the front end of land use planning. Parks Canada was the only agency with a fully integrated wildfire management program guided by plans for each national park where wildfires need to be managed.

Implementing FireSmart initiatives and increasing the amount of managed wildfires on the landscape will take time to implement due to the need for capacity and capability re-alignment. Local governments in Canada have been slow to implement FireSmart principles because of their focus on other priorities. Only Quebec has legislation stipulating regulatory standards to guide local governments to reduce wildfire risk (Raikes and McBean 2016). The paradigm shift is therefore contingent on agencies continuing to strengthen their suppression capacity and capability. This anchoring prerequisite hence forms the base of the paradigm shift triangle (Fig. 2.5).

Although ecological benefits are usually communicated as the rationale for moving towards a risk-based appropriate response approach (Fig. 2.5), the rising cost of wildfire operations is a motivating factor. Managing wildfires, and in particular large, high, intensity wildfires using a risk-based appropriate response approach can result in significant cost savings (Calkin et al. 2014).

The paradigm shift requires agencies to make science-informed decisions but funding for wildfire research has been a major barrier. Martell (2007) also suggested that wildfire managers and operational research specialists need to increase the collaborative development of applied decision support systems to support the implementation of the Canadian Wildland Fire Strategy (CWFS) (Canadian Council of Forest Ministers 2005). A blueprint for wildland fire science in Canada (Sankey 2018) aims to increase horizontal collaboration and foster increased investments for innovation and collaborative research to further advance the CWFS by growing the wildland fire science research capacity in Canada.

2.8 Conclusion: A path forward

Progress is being made to adapt incrementally to increasing wildfire threats as they arise, but a horizon scanning and foresight report by MNP (2018) suggests the problem will get much worse. Wildfire impacts are likely to intensify as Canada's climate continues to warm at twice the global warming rate (Government of Canada 2019). Agencies therefore need to move from short-term fixes to transformational change to address the long-term picture. This includes the paradigm shift we described in the previous section, and the need for a risk-based appropriate response approach. Without this approach and the implementation of supportive operating procedures, overly risk-averse decisions will continue to dominate wildfire management operations (Maguire and Albright 2005). Saskatchewan has shown that this barrier to cultural change can be overcome by implementing strategic, performance, and accountability frameworks to guide operational decision making (Government of Saskatchewan n.d.).

Moving national initiatives forward in Canada is a challenge because of the need to reach consensus among the fourteen CIFFC FTP members who all have unique geo-political and social-ecological considerations. Pyne (2007) provides an historic context of how the confederation of provincial, territorial and federal governments, sometimes competing, sometimes cooperating, has forged wildfire management policy in Canada. The consensus approach used in Canada can address future wildfire management challenges but agencies need to strengthen communication, cooperation, coordination and collaboration (Martin et al. 2016). CIFFC in particular, has the opportunity to increase its current role of facilitating and supporting pan-Canadian cooperation and coordination (Canadian Interagency Forest Fire Centre 2019).

More can also be done by agencies to engage other departments, local governments, non-profit organizations, and the private sector to combine efforts to attain shared goals. This includes the further development of national standards, guidelines, terminology, decision support tools, and preparedness strategies. Further gains can also be made by enhancing data-sharing and integration, obtaining collaborative support and leveraged funding to address operational wildfire research gaps, and developing innovative, integrated solutions.

Specific gaps in preparedness research include understanding the optimal level and configuration of resources required in Canada to be better prepared to meet future needs. Is there a business model for establishing regional equipment caches and air tanker bases, and how can fire weather and fire occurrence forecasting be improved? An increase in the frequency of extreme fire weather events in the future will require greater intergovernmental collaboration (Curnin et al. 2015), and the application of new levels of preparedness and management (Canadian Climate Forum 2014).

The dependence on capacity extension through international assistance and external staffing will continue and likely increase unless Canada is strategically prepared nationally to manage future wildfire threats (B.J. Stocks Wildfire Investigations Ltd 2013). As the frequency of more intense wildfires increase and new wildfire prone areas emerge (IPCC 2019) the global competition for limited suppression resources too will increase.

In 2016, a review and renewed call to action of the Canadian Wildland Fire Strategy (Canadian Council of Forest Ministers Wildland Fire Management Working Group 2016a) identified the need to increase preparedness capacity by i) enhancing firefighting capacity including the training and employment of Indigenous Peoples; ii) renewing critical assets (e.g. aircraft, equipment and also highly qualified wildfire management personnel); iii) maintaining or replacing critical infrastructure (e.g. communication and weather station networks, initial attack and air tanker bases); and iv) developing innovative solutions to overcome human resource challenges (e.g. staff recruitment and retention, skills upgrading) (Canadian Council of Forest Ministers Wildland Fire Management Working Group 2016a). Most resource mobilization in Canada supports the response phase. Since the highest return on investment is at the preparedness phase, we suggest that agencies also consider the mobilization of resources to support both response and readiness.

Transformational change within wildfire management to confront a rapidly changing world and implement the CWFS necessitates new skills upgrading. As wildfire events become more complex, and more decision support tools become available, enhanced training and education will be required to strengthen wildfire management capability. This includes understanding the authorized roles and responsibilities of local, provincial, territory and federal agencies during a complex, multi-agency wildfire emergency. This component of wildfire preparedness requires agencies to foster and support a partnership culture before rather than during a disaster. As emergencies other than wildfire also increase in frequency and intensity, we foresee more governments considering the adoption of a single public safety agency under one ministry as a viable solution to improve internal coordination and cooperation. Although restructuring allows for a single point of contact it does not necessarily resolve organizational edge issues.

While this paper focuses on Canada and agency preparedness, the lessons learned and the renewed approach to implement the CWFS will be of interest to other countries and in particular those who have an emerging wildfire problem. The CWFS addresses the need for increased preparedness capacity but also identifies the need to enhance prevention and mitigation and support resilient communities through FireSmart initiatives. Lastly, while we acknowledge much has been done in Canada on interagency multi-level cooperation, wildfire management agencies are simply not doing it fast enough to mitigate future disasters effectively. We also recognize that governments are challenged to address many societal issues but the wildfire problem is not going away.

2.9 Acknowledgements

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3. Statistical surveillance thresholds for enhanced situational awareness of spring wildland fire activity in Alberta, Canada

Cordy Tymstra, Douglas G. Woolford, Mike D. Flannigan

3.1 Abstract

Wildland fire disasters across Canada and globally are increasing in frequency. Alberta's spring wildfire season is a particularly challenging period. Situational awareness of the wildfire environment is critical for wildfire management agencies to be prepared when extreme events occur. We propose the use of simple initial attack (IA) and being held (BH) escape surveillance charts in near-real time with thresholds as tools for enhancing and tracking situational awareness. Since the discrete data sets we used are zero-inflated and over-dispersed we chose to model the exceedances over a threshold. We also used preceding December sea surface temperatures (SST) of the Pacific Ocean as an indicator of persistent spring wildfire activity. Our analysis indicates the tracking of IA and BH escapes and SST can provide additional decision support as part of an early warning system of spring wildfire risk.

3.2 Introduction

Natural disasters and catastrophes[1] are increasing globally in frequency, and cost. Based on insured losses in 2017, wildfires worldwide totaled a record $14.62 billion USD, and in California, United States alone they resulted in the fourth costliest natural catastrophe ($12 billion USD) (Swiss Re Institute 2018). British Columbia, Canada also experienced a disastrous wildfire season in 2017 when 1,351 wildfires burned a record 1.2 million ha and displaced 65,000 residents (Abbott and Chapman 2018). In 2016, the 589,552 ha Horse River Wildfire in Alberta, Canada resulted in insurance claims totaling $3.7 billion (Insurance Bureau of Canada 2017).

[1] Major disasters resulting in $25 million or more in insured property losses (Insurance Information Institute 2018)

Large wildfires are not uncommon in Canada, particularly in the boreal forest (Tymstra 2015). On average, Canada experiences 8,000 wildfires and 2.25 million ha burned each year. Historically, about 20% of the time the total annual area burned has exceeded 4 million ha

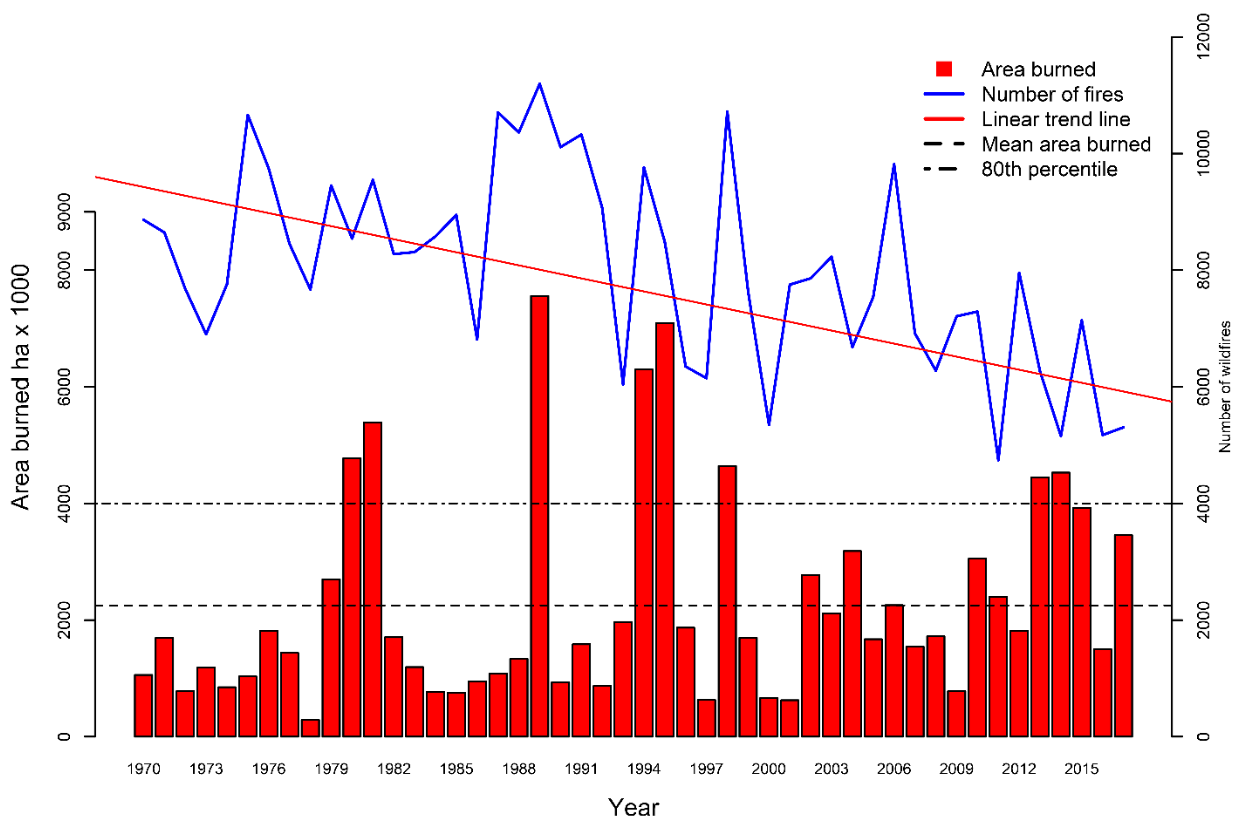

Figure 3.1 The annual number of wildland fires and total area burned in Canada over the period 1970 – 2017.

(80th percentile) (Fig. 3.1). A commonly used definition for a large wildfire in Canada is a wildfire whose final size was 200 ha or more (Stocks et al. 2002). For the 1959 – 1997 period about 3% of wildfires in Canada exceeded 200 ha in size but they accounted for 97% of the area burned (Stocks et al. 2002). Although the number of wildfires in Canada, with a few regional exceptions, has been trending downward, the number of wildfire disasters have been trending upward by decade since 1980 (Public Safety Canada 2018). During the 2010 – 2017 period 78% of the national burned area occurred in western Canada (Yukon Territory, Northwest Territories, British Columbia, Alberta and Saskatchewan) (Natural Resources Canada 2018).

Early warning of fire danger conditions is critical to ensure preparedness activities contribute to preventing and mitigating wildfire disasters. Situational awareness requires having a perception and comprehension of the current situation and then projecting it into the future to provide early warning and preparedness decision support (Endsley 1995). Since it can take two weeks or longer to mobilize resources from other countries, wildfire management agencies need a situational awareness based on 10 – 14 day outlooks of weather and fire occurrence. The foundation for early wildfire danger warning in Canada is the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al. 1989; de Groot et al. 2015). The two main components of the CFFDRS are the Fire Weather Index (FWI) Subsystem which is widely applied around the world (de Groot et al. 2015), and the Fire Behaviour Prediction (FBP) Subsystem. The FWI Subsystem provides a relative rating of fuel moisture codes representing fuel layers, and fire behaviour indices. The FBP Subsystem incorporates the FWI System outputs to provide quantitative assessments of fire behaviour for specific fuel types across Canada.

Assessing wildfire environment conditions in early spring solely using the CFFDRS outputs can be a challenge if the full complement of weather stations are not yet operational. Since the CFFDRS fuel moisture codes are not direct measurements of the fuel layers, fuel moisture code validation may be necessary to adequately account for the over-winter precipitation effect on fuel moisture, and accurately start the FWI fuel moisture codes in the spring. Foliar moisture content too, can influence spring wildfire behavior, but the default date for minimum Foliar Moisture Content (FMC) may be inaccurate because the actual date of minimum FMC can shift up to 4 – 5 weeks from year to year (Van Wagner 1967).

The spring season can therefore be a particularly challenging wildfire danger period for wildfire management agencies across Canada. In Alberta, disastrous spring wildfire seasons occurred in 1995, 1998, 2001, 2002, 2011 and 2016 when environmental conditions (low foliar moisture content, no green-up, low relative humidity, and strong, dry winds) supported extreme wildfire behaviour (Fig. 3.2). Wildfire starts in Alberta during the month of May alone accounted for 23% of the total number of wildfires, and 51% of the total area burned for the entire wildfire season (March 1 - October 31) from 1990 to 2017. Most (81%) of the May wildfire starts are human-caused.

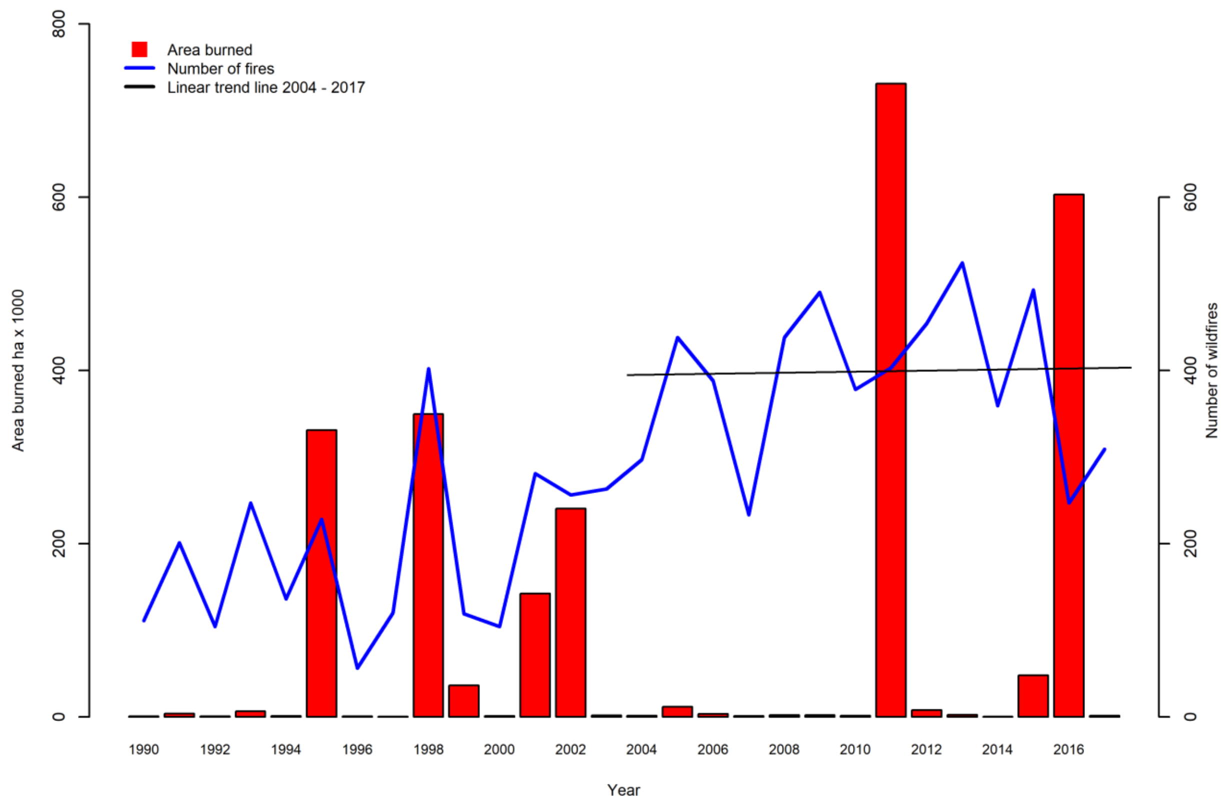

Figure 3.2 Annual total number of wildfire starts in May and the total corresponding total area burned from these wildfire starts in Alberta over the period 1990 – 2017. A linear trend line for the number of wildland fire starts is also shown, starting from 2004 when reporting procedures changed.

There is subsequently a strong need to develop tools in addition to the CFFDRS to provide enhanced situational awareness during the challenging spring wildfire period between snowmelt and green-up. Our work is motivated by what appears in the health sciences literature, including the various approaches and statistical models used to forecast disease outbreaks. Examples include generalized linear modeling (Goldstein et al. 2011), hierarchical statistical modeling (Mugglin et al. 2002), and autoregressive integrated moving average modeling (ARIMA) with climatological parameters (Soebiyanto et al. 2010) for predicting influenza outbreaks; logistic regression modeling for West Nile Virus incidence prediction; statistical/machine learning using least absolute shrinkage and selection operator (LASSO) methods (Shi et al. 2016), Knorr-Held two-component (K-H) modeling (Earnest et al. 2012), and Poisson multivariate regression modeling (Hii et al. 2012) for predicting dengue fever. Thomson and Mason (2012) used seasonal climate forecasts from multi-modal ensembles to predict malaria outbreaks. Surrogate data such as social media (Yang et al. 2013), over-the-counter drug sales (Das et al. 2005), and absenteeism in school (Kara et al. 2011), have also been used to predict infectious disease outbreaks.

Unlike disease surveillance and other biosurveillance methods and applications, the literature on statistical approaches applied to provide early warning of potential surges in wildfire activity, is comparatively sparse. Taylor et al. (2013) summarized the methods used to predict wildfire occurrence (arrival) and wildfire behavior (growth). Examples of statistical methods used to provide wildfire management decision support include the estimation of wildfire risk using probability based models (Preisler et al. 2004); application of a mixture modeling framework to monitor historical trends in lightning wildfire risk (Woolford et al. 2014); development of an early warning wildfire risk system based on modelling vegetation green-up using satellite observations (Pickell et al. 2017); and the use of machine learning (artificial neural network) to predict weather patterns associated with extreme wildfire events (Lagerquist et al. 2017).

The objectives of this paper are to conduct an exploratory analysis of historical wildland fire records to examine methods for short-term situational awareness and to explore for possible teleconnection signals between pre-season sea surface temperatures (SST) and characteristics of wildfire activity in the spring. Our study region is the entire legislated Forest Protection Area in Alberta over the period 1990 to 2015 (Fig. 3.3).

We focus our exploratory analysis on process control and the operational application of control charts. Syndromic surveillance (Fricker 2013) with statistical thresholds is shown to be a viable approach to enhance the situational awareness of potential spring wildfire activity in Alberta. Syndromic surveillance uses nowcasting data to continuously monitor, analyze, and detect data aberrations that signal a current or likely event change.

We also explore the application of a simple metric to forecast the persistence of spring wildfire activity in Alberta based on the association between December sea surface temperature

Figure 3.3 Forest Protection Area within the Province of Alberta, Canada

anomalies in the south-east Pacific Ocean, and wildfire activity in the spring. When the predominantly eastern trade winds over the south-east Pacific Ocean weaken, warm water flows in a reverse west to east pattern (Rasmusson and Wallace 1983). This phenomena, called El Niño, causes a shift in atmospheric circulation which influences weather patterns. In western Canada this results in above average temperatures in the winter and spring.

We hypothesize that during such ENSO (El Niño Southern Oscillation) warming events the wildfire activity in early spring is an indicator of persistent wildfire activity into late spring. Skinner et al. (2006) reported a positive correlation between ENSO and the Pacific Decadal Oscillation (PDO), and Shabbar et al. (2011) found a lagged association of forest fire severity conditions with ENSO warming events across Canada's boreal forest. Beverly et al. (2011) also found a coupling of the large wildfire activity in Canada with the Atlantic Multidecadal Oscillation (AMO). They suggested that wind may be a critical component of this coupling. At a provincial level, wildfire activity in British Columbia was correlated positively with ENSO and PDO indices (Wang et al. 2010).

3.3 Data

3.3.1 Initial Attack and Being Held Escapes

When initial attack (IA) resources are dispatched to a wildfire in Alberta, the objective is to initiate suppression activities before the wildfire exceeds 2.0 ha in size. Wildfires that exceed 2.0 ha in size before IA resources arrive are referred to as IA escapes. If a wildfire can be contained by 1000 h the day following its initial assessment, a second objective called Being Held (BH) is achieved. Wildfires with a BH status are not expected to increase in size based on the current fire environment conditions. If the BH objective is not attained the wildfire is referred to as a BH escape (Government of Alberta 2018b).

The IA and BH attribute data, and other data characterizing a wildfire from ignition to extinguishment (Fig. 3.4) are entered in near-real time in a system used in Alberta called FIRES (Fire Information and Resource Environment System). Data entry into FIRES began in 1990. Exported data from FIRES were obtained from the Wildfire Management Branch for the 1990 – 2017 period. We reserved the years 2016 and 2017 for model testing purposes.

[redacted]

Figure 3.4 Wildfire attribution in Alberta’s FIRES system from ignition to extinguishment.

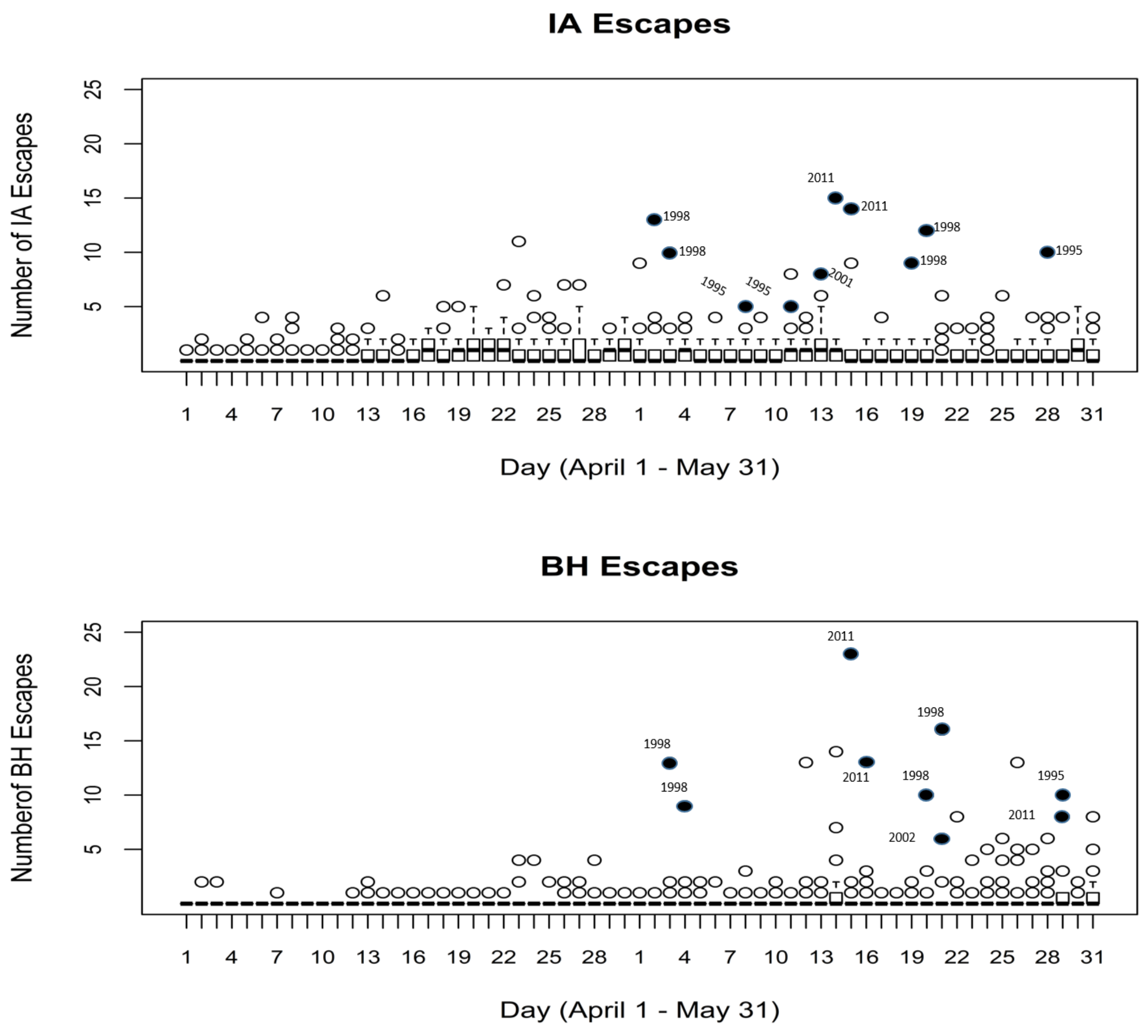

Figure 3.5 Boxplots of daily IA and BH escapes in Alberta for April and May 1990 - 2015. The years with the highest total area burned (refer to Fig. 3.2) that had more than 4 daily IA escapes and more than 5 BH escapes are labelled and identified as black outliers.

In 1995, the minimum reporting wildfire size was reduced from 0.1 ha to 0.01 ha. Then in 2004, the reporting procedure changed to include permit related Order to Remove (OTR) escapes and more than 5 BH escapes are labeled and identified as black outliers. OTR wildfires (usually residents using burn barrels) and abandoned illegal campfires (called XA wildfires) that took less than 15 minutes to extinguish. An increase in the number of reported wildfires beginning in 2004 is evident in Fig. 3.2. Although OTR and XA identifier attributes are not included in FIRES, these wildfires did not affect the IA and BH escape data we used because they are relatively easy to extinguish.

The IA and BH escape data are zero-inflated and long-tailed (Fig. 3.5). Estimates for the probabilities of IA and BH success and escape for the 1990 to 2015 period for the month of May are summarized in an empirical probability tree (Fig. 3.6). During the 1990 – 2015 period, a total of 7,523 wildfires arrived in Alberta during the month of May. Approximately 91% of these wildfires were initial attacked before they exceeded 2.0 ha in size (IA Success). Of these 6,698 IA success wildfires approximately 97% were contained (BH Success) by 1000 h the following day of their assessment. The probability of a wildfire arrival being successfully initial attacked (IA Success) and contained (BH Success) is about 89%.

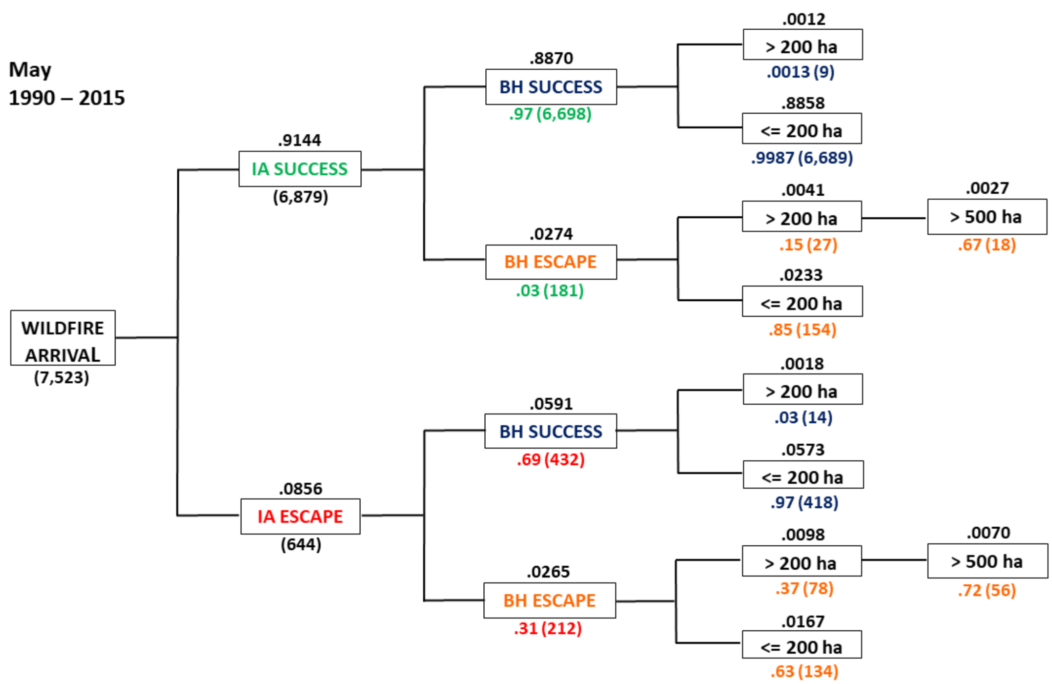

Figure 3.6 Empirical probability tree for May wildfire Initial Attack (IA) and Being Held (BH) successes and escapes for the period 1990 – 2015 when 7,523 wildfire arrivals were reported in Alberta for the month of May. Joint probabilities are given above each box, and group (by colour) probabilities and number of successes and failures are given below each box.

The third and fourth branches in Fig. 3.6 include the probabilities of those wildfires escaping BH and exceeding 200 and 500 ha in size. Only 74 of the 7,523 wildfires in May grew larger than 500 ha in size. Such wildfires are costly and challenging for wildfire management agencies to control. For the same period (1990 – 2015) the month of April in comparison, had only 7 wildfires that grew larger than 500 ha in size. This follows the Pareto Principle (Pareto 1906) where a small number of wildfires escape and cause the most impact. Later, we present the results of fitting parametric models for the IA and BH escape distributions, and illustrate a simple technique for syndromic surveillance based on the quality control literature.

3.3.2 El Niño Southern Oscillation Teleconnections

Besides the need to develop syndromic surveillance methods for near real-time monitoring for tactical wildfire management decision support there is also a strong need to identify longer-term warning systems to support more strategic decisions such as seasonal staffing and the hiring of contract wildfire suppression aircraft. We thus obtained monthly sea surface temperature (SST) anomalies for an area in the Pacific Ocean referred to as Region 3.4 (5° N – 5° S, 120° – 170° W) from the United States National Weather Service Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/detrend:nino34:ascii:txt). The anomalies are the departures from the climatological monthly means for the 1981 – 2010 period. During strong El Niño events the warming of the central and east-central equatorial Pacific Ocean typically peaks during December (Trenberth 2016). We chose the December SST anomalies (°C) to indicate the likely persistence of environmental conditions and wildfire activity in the spring.

Implementing advanced readiness such as the activation of fire bans and area closures, increasing detection efforts, and mobilization of suppression resources in anticipation of a wildfire threat is usually made when thresholds (i.e. indicators that prompt a response) are reached. These thresholds however, are based primarily on expert opinion. In what follows we describe two approaches that can be used to develop early warning products in addition to the CFFDRS outputs to trigger advanced preparation to manage the impacts of a potential disastrous wildfire event.

3.4 Methods

3.4.1 IA and BH Escapes

We consider wildfire starts as akin to the arrivals of customers or patients that need servicing. The wildfire management response to wildfire arrivals can therefore be viewed as a process with associated quality or process control (i.e. IA and BH objectives). We investigated the various statistical process control (SPC) charts used in health-care (Woodall et al. 2012) for their application to the wildfire management response process. Quality control charts for count type data use statistical model parameters to set upper and lower thresholds called control limits, to identify when a process is not in control (Montgomery 2013). The time series surveillance approach with control limits that we use is similar to an attribute control chart (c-chart) with a constant size inspection unit. Our inspection unit is the entire population for a province-day. Since the lower control limit is not of concern to wildfire managers we only estimate the upper control limit.

We focused on detecting aberrations (outliers) in the number of IA and BH escapes during the months of April and May for the 1990 – 2015 period (Fig. 3.5) using daily counts, and rolling 2- and 3-day sums. Two years (2016 and 2017) were reserved for a post-evaluation of the threshold selection and theoretical operational decision support. The rolling 3–day sum accounts for the long weekends in April and May (Canadian statutory holidays). Sums were selected because they are easily interpreted by operational wildfire management staff.

To understand the underlying structure and distribution of our discrete data we used exploratory data analysis and parametric model fitting of the distributions and their tails. We fitted Poisson, Negative Binomial, Zero–Inflated Poisson (Fig. 3.7), and Zero–Inflated Negative Binomial distributions to the IA and BH count escape data. Since our data are zero-inflated and over dispersed, and because our objective is to derive operational early-warning thresholds of spring wildfire activity, we chose to apply univariate extreme value theory (EVT) and the Pareto Principle using the peak over threshold (POT) approach to model IA and BH escape risk. Introduced by Goda (1985), the POT technique models exceedances (peaks) of high, predetermined thresholds, and approximates the distribution of these right-tail outliers using the generalized Pareto distribution (GPD) (Balkeman and de Haan 1974; Pickands 1975). The cumulative density function of GPD is defined as:

$$F(x) = 1 - \left(1 + \frac{\xi x}{\sigma}\right)^{\frac{-1}{\xi}}$$

where $\sigma > 0$ and $\xi \in \mathbb{R}$ are scale and shape parameters and x is the distance above the predetermined exceedance threshold of interest. There are three forms of Pareto distribution to characterize the behaviour of extremes: Gumbel ($\xi = 0$), Frechét ($\xi > 0$) and Weibell ($\xi < 0$).

We applied the POT technique to estimate statistical surveillance thresholds using the R package POT (Ribatet 2019). The threshold exceedances were then fit to a GPD using the maximum likelihood estimation (MLE) method in the R package evir (Pfaff 2018). This approach allows for the calculation of IA and BH estimates and confidence intervals for various quantile and confidence levels.

As indicated, the POT approach requires one to set an exceedance threshold. Although the POT package includes several functions for threshold estimation we chose percentiles, and the kurtosis method proposed by Patie (2000) to estimate IA and BH escape thresholds. Chen et al. (2015) used this kurtosis method to estimate threshold values for influenza outbreaks. The percentile levels we chose for our exploratory POT analyses were based on the 68–95–99.7 empirical rule. We include percentile thresholds as potential alternates to using thresholds based on the kurtosis since they are straightforward for end users to identify and associate with upper control limits.

Kurtosis and skewness are non–normality measures of a distribution's “tailedness" and “asymmetry" respectively (Groeneveld and Meeden 1984). We are interested in the number of IA and BH escape extreme values that are outside of the normal range (i.e. a kurtosis value larger than that associated with a normal distribution). Univariate normal distributions have a Pearson's kurtosis value of 3. Kurtosis minus 3 refers to the excess kurtosis from an expected re-scaled value of 0 for the normal distribution. Excess kurtosis is defined as:

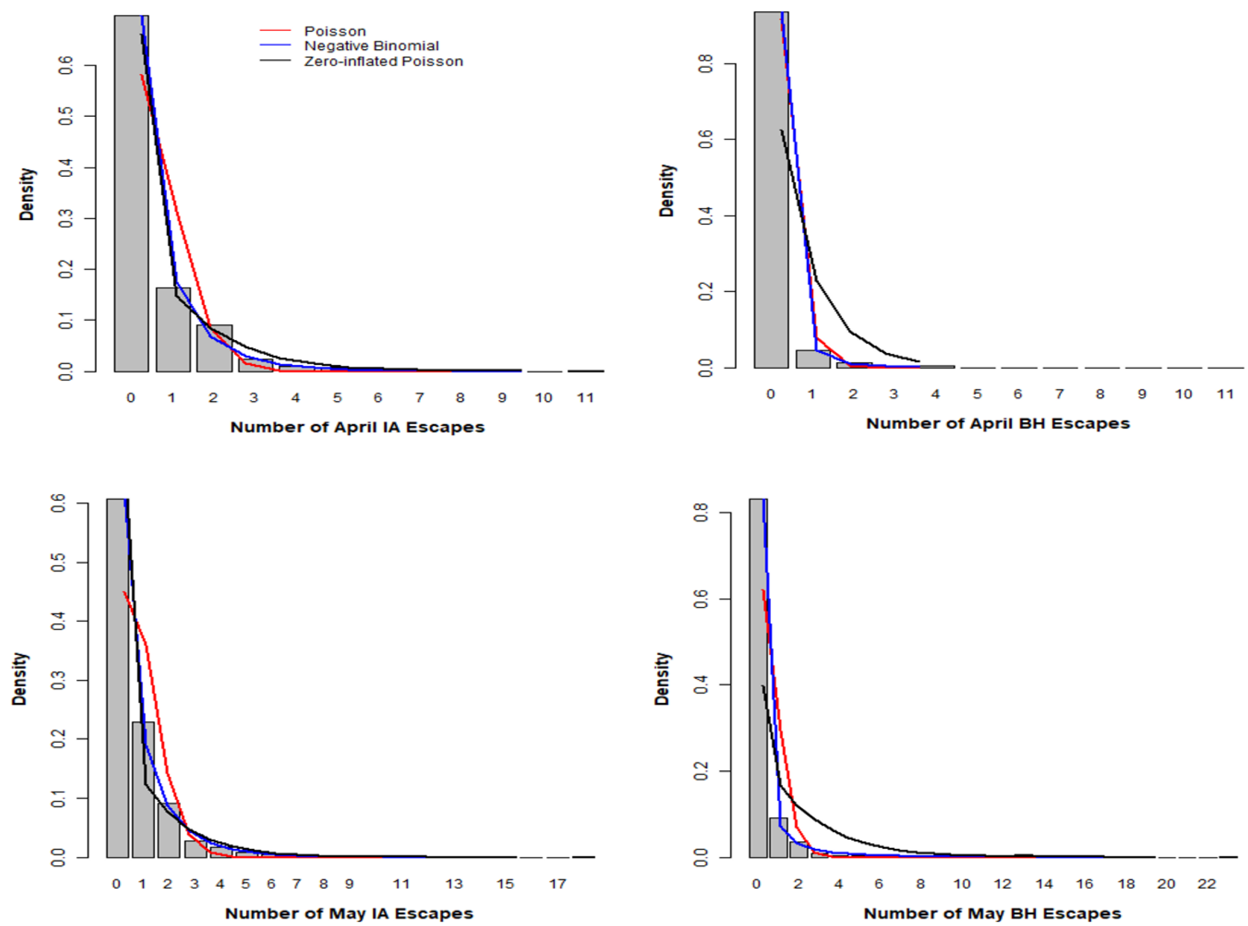

Figure 3.7 Poisson, Negative Binomial and Zero–inflated Poisson fit to the April (top) and May (bottom) IA (left) and BH (right) escape data for the 1990 – 2015 period.

$$\hat{k} = \frac{\sum_{i=1}^{N} \frac{(X_i - \bar{X})^4}{n-1}}{s^4}$$

where X_i is the i^{th} X value, $\bar{X}$ is the mean, s is the sample standard deviation, and n is the sample size.

Skewness is defined as:

$$S_k = 3\frac{(\bar{X} - \tilde{X})}{s}$$

where $\tilde{X}$ is the median.

To calculate thresholds using the kurtosis method, we applied four steps to each of our 24 datasets (see Tables 3.1 and 3.2). Excess kurtosis β_2, skewness μ_n, and variance s_n^2 were first calculated. In the second step the observation of X_i maximizing $(X_i - \mu_n)^2$ was removed. The first and second steps were repeated until the excess kurtosis for the data subset was less than 3. The largest remaining X_i in the data subset was then chosen as the threshold.

3.4.2. El Nino Southern Oscillation Teleconnections

To supplement the nowcasting of IA and BH escape thresholds and provide additional situational awareness we also investigated the use of teleconnections data to provide a persistence forecast of the wildfire environment conditions. We plotted the December sea surface temperature anomaly for Region 3.4 in the equatorial Pacific Ocean from 1960 to 2017 (Fig. 3.8). Since our IA and BH escape data are not normally distributed we used an ordinal measure of association to test our hypothesis that a positive teleconnection association exists between early and late spring wildfire activity. The Spearman Rank Correlation Coefficient (Spearman's ρ) was used to determine the strength of nine associations (ρ) of wildfire activity (number of wildfires and area burned) between various combinations of time periods in the spring (month and half month periods) and the December SST anomalies (° C) for Region 3.4 in the equatorial Pacific Ocean. The very strong (> 1.99 ° C), strong (1.5 – 1.99 ° C) and moderate (1.0 – 1.49 ° C), weak (0.5 – 0.99 ° C) categories of SST anomalies (Null 2018) were used to filter and recalculate Spearman's ρ for 9 of the 28 years when a warming ENSO event occurred.

To continue this exploratory data analysis, scatterplots (Fig. 3.9) were made for selected associations with higher reported Spearman's ρ (number of wildfires in April versus May, number of BH escapes in April versus May, number of BH escapes in April period 2 versus the number of BH escapes in May period 1, and the number of BH escapes in May period 1 versus period 2). The April period 1 includes days 1 to 15, and period 2 includes days 16 to 30. The May period 1 includes days 1 to 15 and period 2 includes days 16 to 31.

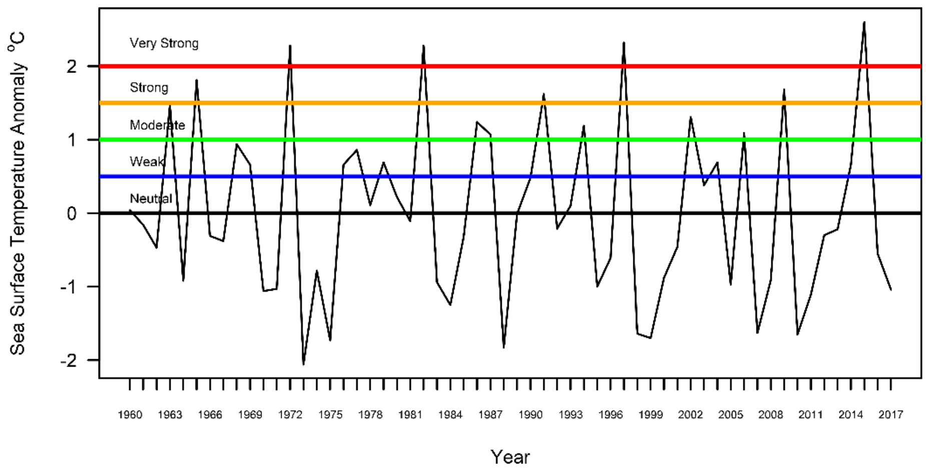

Figure 3.8 December sea surface temperature anomaly for Region 3.4 in the equatorial Pacific Ocean 1961 – 2017.

3.5 Results

3.5.1 Model fitting

The May data set (31 days/26 years = 806 observations) included 643 IA escapes and 383 BH escapes. The score test for zero inflation (van den Broek 1995) indicated these data sets have significantly more zeros compared to the expected number of zeros from a Poisson distribution. This test statistic has a χ_1^2 distribution. The April data set (30 days/26 years = 780 observations) included 422 IA escapes and 67 BH escapes. All corresponding upper tail *p*-values were < .001. We therefore fitted the four data sets to a zero-inflated Poisson (ZIP) distribution (Fig. 3.7). We used Pearson's χ^2 test to assess the goodness-of-fit. The count IA and BH escape data for both April and May did not fit a ZIP distribution (Fig. 3.7). All upper tail *p*-values were again < .001.

To address over-dispersion we fitted our count data to negative binomial and zero-inflated negative binomial distributions. These fits, however, also failed the goodness of fit test with all reported p-values < .001. We did not include the zero-inflated negative binomial fits in Fig. 3.7 because they were such poor fits to these data. Q-Q plots of the resulting fits suggested a lack of fit in the upper tail of these distributions, and the need to model the tails using an extreme

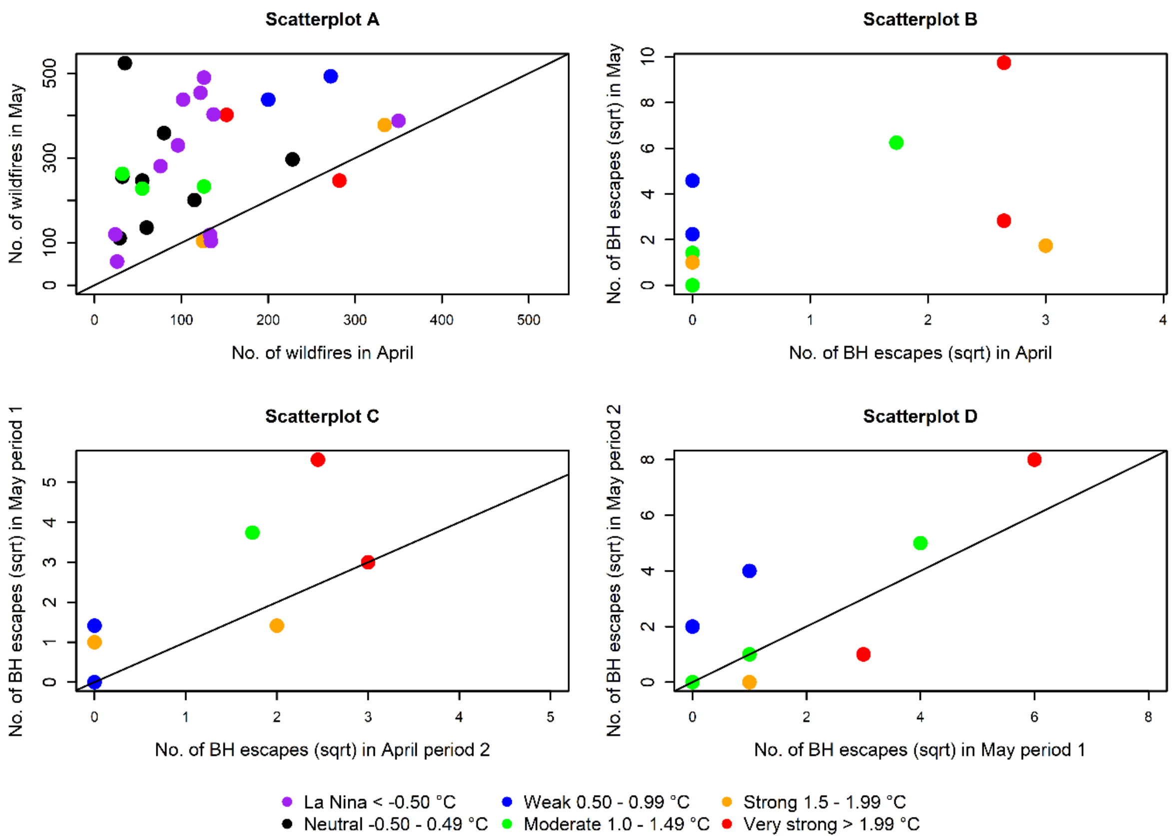

Figure 3.9 Scatterplots of spring wildfire activity in Alberta (1990 – 2017) with December sea surface temperature (SST) anomaly categories. The number of wildfires in April are plotted versus the number of wildfires in May in Scatterplot A. Scatterplots B, C, and D graph square root transformations of the variables. The number of BH escapes (sqrt) in April are plotted versus the number of BH escapes (sqrt) in May (Scatterplot B). Scatterplots C and D plot the number of April and May BH escapes for two different time periods.

value distribution. We chose the generalized Pareto distribution (GPD) and peak over threshold approach.

Varying thresholds were calculated depending on the method used (Tables 3.1 and 3.2). In our opinion the thresholds for the daily and 2– and 3–day rolling sum IA escape data (with zeros) based on the kurtosis method, and the BH escape data (with zeros) based on the 97 percentile method (Tables 3.1 and 3.2) are reasonable because they are supported by wildfire operations experts, and capture those years with severe spring wildfire activity (i.e. 1995, 1998, 2001, 2002, 2011). The calculated May threshold of 10 using the kurtosis method for the 3-day rolling sum of

IA escapes resulted in 28 exceedances (Table 3.1). Threshold values of 9 and 11, in comparison yielded 35 and 21 exceedances respectively. Of the three percentiles, the 95 percentile resulted in IA escape thresholds that were closest to the thresholds calculated using the kurtosis method.

The exceedances data based on a May IA escape threshold value of 10 fit the GPD distribution well as shown in the QQ plot of residuals (Fig. 3.10). The maximum likelihood estimates of the scale and shape parameters are 9.77 (*se* = 2.86) and -0.363 (*se* = 0.23). The 95% CI for these parameters are 4.15 to 15.38 (scale), and -0.88 to 0.09 (shape). We acknowledge that rolling sums are inherently less noisy and fit better than the daily observations. All six QQ plots of residuals from the GPD are good fits for the month of May, including the fit to the daily observations (Fig. 3.10).

We are unable to include similar QQ plots for April due to insufficient data being available to fit the GPD model to IA and BH escapes in that month. We note that, historically, there is much lower wildfire activity in April. This results in daily IA and BH escapes rarely occurring during this month and even when such an event does occur, its corresponding daily escape count is typically very small. This leads to a situation where there are very few threshold exceedances observed for a given threshold value identified by one of the methods and very little variability in the observed counts. Hence, the model cannot be fit. For example, a threshold value of three for BH escapes in April results in only three threshold exceedances (Table 3.2). Note that for each of these instances the corresponding BH escape count was exactly four. With very few observations and little-to-no variability between such observations it is not possible to fit the GPD model in such situations; many more years of data are needed.

Since the kurtosis method resulted in very few threshold exceedances for BH escapes in April, and low threshold values with high numbers of exceedance for BH escapes in May, we added a fourth percentile level (0.97) as noted in Table 3.2. The Wildfire Management Branch in Alberta reported one performance metric in their Department's 2017-18 Annual Report (Government of Alberta 2018a) called the Containment of Wildfires Performance Measure. This performance target is based on the previous five year average of the actual BH achievements. For example, the 2017 target was 97% (2012 – 2016 average), and the actual level achieved that year was 96.8%.

Table 3.1 Initial attack escape thresholds and threshold exceedances for April and May (1990 – 2015).

IA Escapes	68 Percentile Threshold: Exceedances		95 Percentile Threshold: Exceedances		99.7 Percentile Threshold: Exceedances		Kurtosis Method Threshold: Exceedances	
	April	May	April	May	April	May	April	May
IA escapes with zeros	0: 235	1: 130	2: 37	3: 37	7: 1	14: 2	3: 18	3: 37
IA escapes with no zeros	2: 38	2: 58	4: 11	6: 12	8: 1	15: 1	5: 6	5: 16
3-day rolling sum IA escapes with zeros	2: 188	2: 241	5: 39	9: 35	15: 2	26: 3	9: 10	10: 28
3-day rolling sum IA escapes with no zeros	3: 114	3: 166	7: 20	10: 28	18: 2	28: 2	11: 8	12: 19
2-day rolling sum IA escapes with zeros	1: 209	2: 154	4: 32	6: 35	11: 3	21: 2	6: 16	8: 26
2-day rolling sum IA escapes with no zeros	3: 60	3: 98	6: 16	9: 16	13: 1	22: 2	8: 7	8: 26

Table 3.2 Being held escape thresholds and threshold exceedances for April and May (1990 – 2015).

BH Escapes	68 Percentile Threshold: Exceedances		95 Percentile Threshold: Exceedances		99.7 Percentile Threshold: Exceedances		BH Objective (97 Percentile) Threshold: Exceedances		Kurtosis Method Threshold: Exceedances	
	April	May	April	May	April	May	April	May	April	May
BH escapes with zeros	0: 48	1: 135	1: 13	2: 33	3: 3	14: 2	1: 13	4: 22	NaN	NaN
BH escapes with no zeros	1: 13	2: 33	3: 3	13: 3	4: 0	20: 1	4: 0	13: 3	3: 3	4: 22
3-day rolling sum BH escapes with zeros	0: 119	0: 257	2: 16	8: 36	5: 2	32: 3	2: 16	13: 23	NaN	3: 68
3-day rolling sum BH escapes with no zeros	2: 16	3: 68	4: 4	16: 13	6: 0	36: 1	4: 4	23: 7	5: 2	7: 41
2-day rolling sum BH escapes with zeros	0: 86	0: 206	1: 28	5: 35	4: 1	24: 2	2: 1	8: 24	NaN	NaN
2-day rolling sum BH escapes with no zeros	2: 9	2: 62	4: 1	15: 9	5: 1	30: 1	4: 1	17: 6	4: 1	7: 26

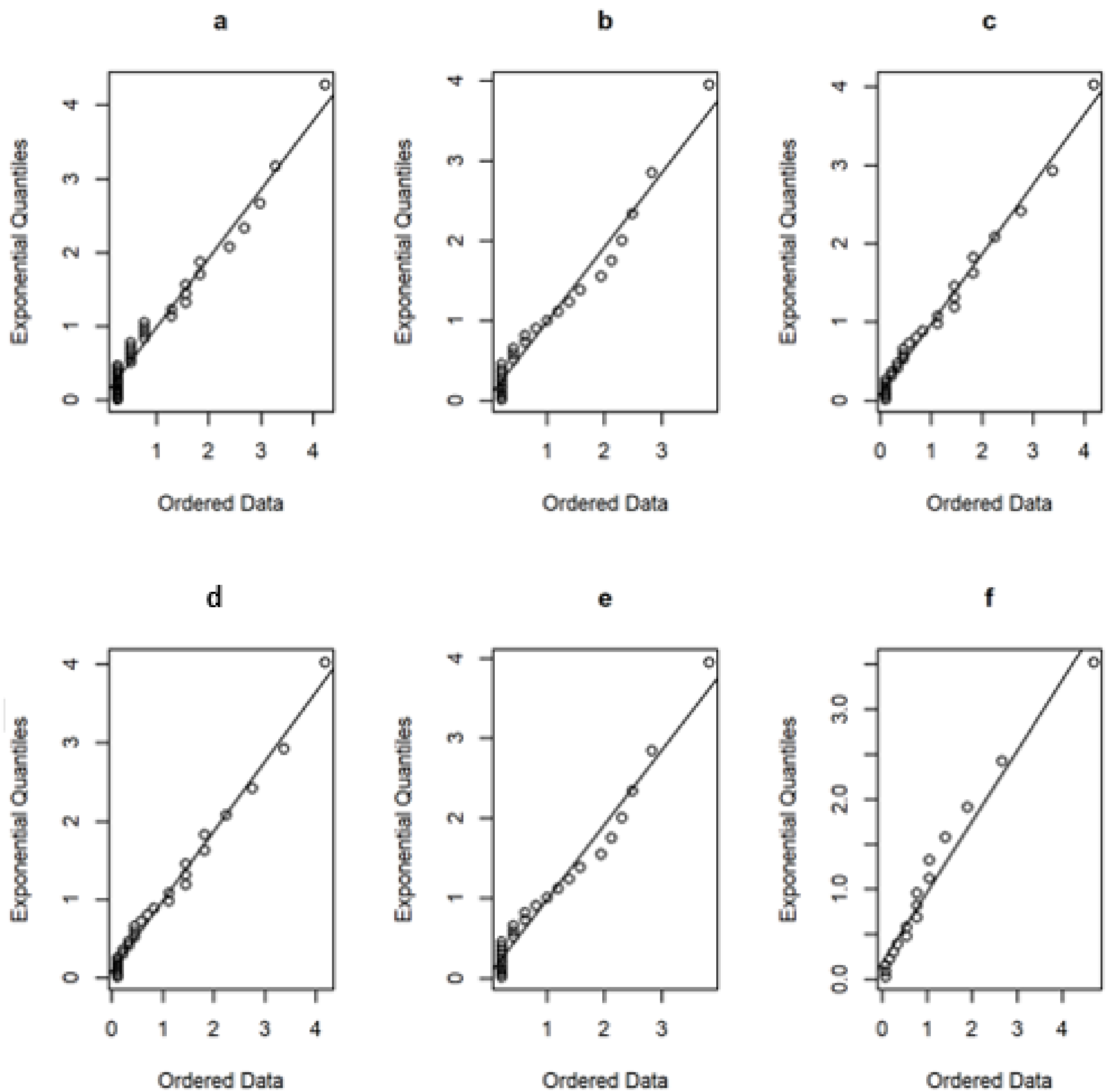

Figure 3.10 QQ plots of residuals for fitting the GPD to 1–, 2–, and 3–day IA (plots a, b, c) and BH (plots d, e, f) escapes in May. Plots a, b, and c use thresholds of 3, 8, and 10 respectively based on the Kurtosis method (with zeros). Plots d, e, and f use thresholds of 4, 8, and 13 respectively based on the percentile method (with zeros).

The calculated May threshold of 13 using the 97 percentile for the 3–day rolling sum of BH escapes resulted in 23 exceedances (Table 3.2). Threshold values of 12 and 14, in comparison yielded 35 and 21 exceedances respectively. The exceedances based on a threshold of 13 also fit the GPD distribution (Fig. 3.10) with scale and shape parameters of 10.57 and -0.28 respectively. We calculated quantile point estimates using a 95% confidence interval for the IA and BH threshold exceedances. The 0.98 quantile estimate of May IA escapes (3–day rolling sum) is

17.48 with lower and upper confidence intervals of 16.01 and 20.87. This estimate occurs once in about nine years. The 0.97 quantile estimate of May BH escapes (3–day rolling sum) is 22.99 with lower and upper confidence intervals of 19.68 and 28.25. This estimate also occurs once in about nine years.

We focus our results on the month of May because it is a more critical month than April. On average only 7% of the days in April have one or more BH escapes. Higher extreme values of daily BH escapes occur in May (max = 23) compared to April (max = 6). More BH escapes occur in May because wildfires in April are usually easier to contain because of higher fuel moisture levels. The daily BH/IA escape ratio increased from 0.19 in April to 0.60 in May. The extreme outliers of daily IA and BH escapes in Fig. 3.4 show a buildup that begins at the start of May, peaks during the snow-melt to start of green-up period (second to third week of May), and tapers during the last week of May when green-up occurs.

Fig. 3.11 includes IA and BH escape charts for 1995, 1998, 2011, and 2016. Two years (2016 and 2017) were reserved for post-evaluation; 2017 was excluded from Fig. 3.11 because like 2016 the IA and BH escapes did not surpass the thresholds. This in itself supports situational awareness but no early warnings are evident during 2016 and 2017 using the thresholds calculated based on the 1990 – 2015 period. However, examples of early warning for other years are evident in Fig. 3.11. Alberta had a disastrous spring wildfire season in 1995. The plotted May 1995 IA escapes show a ramp up period before the 3–day sum peaked on May 8. This is an example of early warning. Another early warning is evident just before the second 3–day sum peak on May 29. The number of 3-day sum BH escapes in comparison do not exceed the threshold until May 29 indicating that most of the earlier wildfires were contained by 1000 h the following day.

In 1998 there was no early nowcast warning when the daily BH escapes peaked on May 3 (13 escapes) and May 21 (16 escapes). The second peak was coincident with the extended May holiday weekend and subsequent increase in recreational activities in the Forest Protection Area. The very strong El Niño that occurred during the winter of 1997/98 continued into the spring and contributed to the disastrous spring wildfire season.

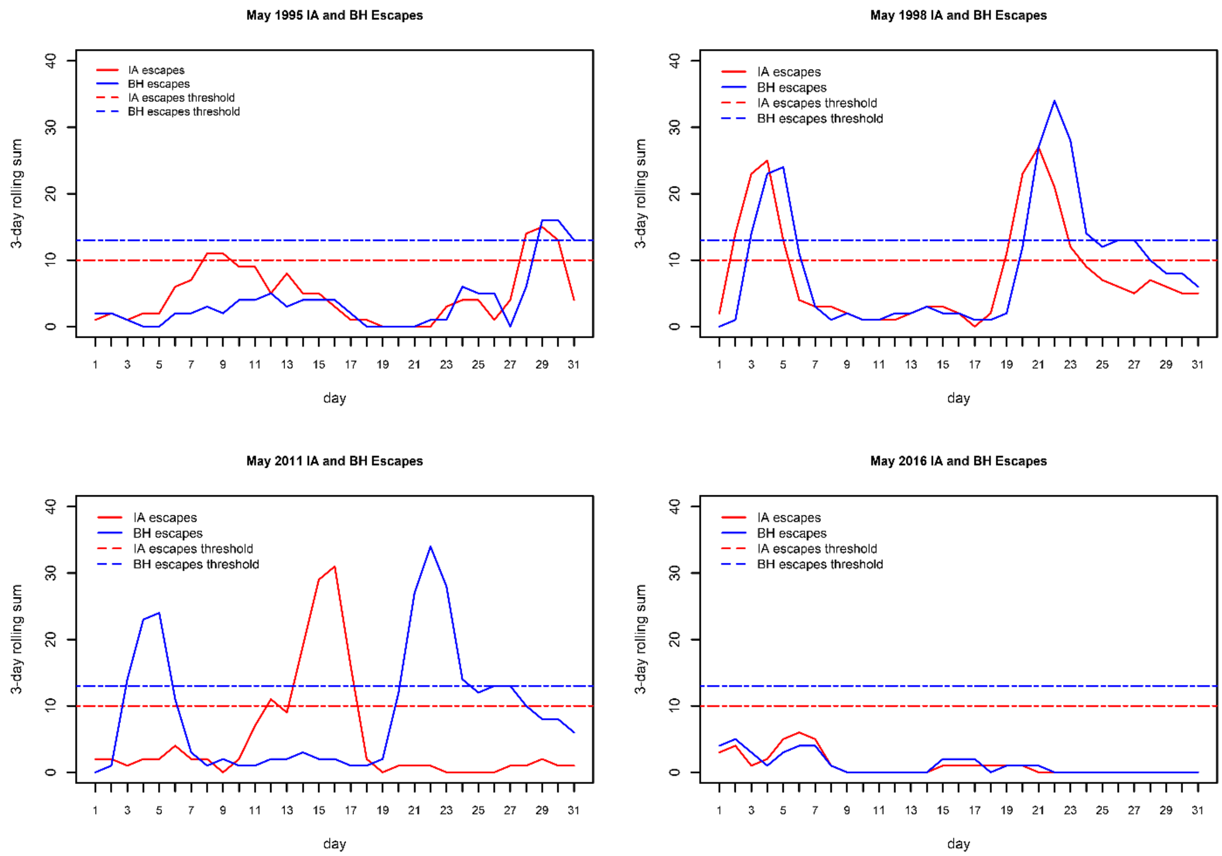

Figure 3.11 Rolling 3–day sum of IOA escapes in May for 1995, 1998, 2011, and 2016 with corresponding threshold lines.

No El Niño event occurred during the 2010/11 winter yet the following spring wildfire season that followed was also disastrous due to the influence of a dry Arctic high pressure system and accompanying strong southeast winds. An early warning is evident on May 11. This early warning when combined with the occurrence of a very strong El Niño during the winter of 1997/98, indicated the persistence of very high to extreme environment conditions and likely upward trend in spring IA and BH escapes. During the first week of May, wildfires were successfully initial attacked but they could not be contained.

3.5.2 El Niño Southern Oscillation Teleconnections

The Spearman's ρ values in the highlighted cells in Table 3.3 are significant at $\alpha = 0.05$ significance level. The critical values for Spearman's ρ (one-tail) are 0.375 ($n = 28$) and

0.786 (n = 9). The number of BH escapes in May period 2 is associated by rank with the number of BH escapes in May period 1 for all years. This association however is stronger when the subset of years is used when moderate to very strong December SST anomalies occurred. There is also a positive association between the number of BH escapes in May period 2 and the number of BH escapes in May period 1.

Table 3.3 Spearman Rank Correlation Coefficient (ρ) of spring wildfire activity and December sea surface temperature anomaly in Region 3.4 in the equatorial Pacific Ocean, with a comparison of all twenty-seven years, and nine teleconnection filtered years. The ρ values in the highlighted cells are significant at α = 0.05.

Spearman Rank Correlation Coefficient 1990 – 2017	**ρ n = 28**	**ρ n = 9**
Number of wildfires in April vs Number of wildfires in May	0.38	0.52
Number of wildfires in April (> 4 ha) vs Number of wildfires in May (> 4 ha)	0.06	0.53
Area burned (ha) in April vs Area burned (ha) in May	0.16	0.32
Number of IA escapes in April vs Number of IA escapes in May	0.08	0.26
Number of BH escapes in April vs Number of BH escapes in May	0.40	0.47
Number of IA escapes in April Period 2 vs Number of IA escapes in May Period 1	.001	0.32
Number of BH escapes in April Period 2 vs Number of BH escapes in May Period 1	0.51	0.80
Number of IA escapes in May Period 1 vs Number of IA escapes in May Period 2	0.20	0.62
Number of BH escapes in May Period 1 vs Number of BH escapes in May Period 2	0.38	0.71

We also used scatterplots to visually explore spring wildfire activity and December SST anomalies. Four associations of spring wildfire activity are included in Fig. 3.10. The x axis is the early time period and the y axis is the later time period. The December sea surface temperature anomaly categories are represented by colour (Purple = La Niña (≤ -0.5 °C), black = neutral (0.49 – -0.49 °C), blue = weak (0.50 – 0.99 °C), green = moderate (1.0 – 1.49 ºC), orange = strong (1.5 – 1.99 °C), and red = very strong (> 1.99 °C).

As expected, Scatterplot A (Fig. 3.9) shows there are more wildland fires in May than in April. There are also no years with a high number of wildland fires in April followed by a low number of wildland fires in May. When the number of April wildland fires exceed 135, the following May wildland fires exceed 200 (mean = 380). Scatterplot C indicates the number of BH escapes in May period 2 is associated with the number of BH escapes in May period 1. No strong patterns are evident with the SST categories, other than the very strong El Niño events show wildland fire activity in April persisting into May.

3.6 Discussion

During a full suppression response, wildfire management agencies aim to quickly keep wildland fire arrivals small in size. This is accomplished by determining the number, type, location and readiness status of suppression resources required in anticipation of the forecasted wildfire environment conditions and wildfire load for tomorrow (active wildfires plus new wildfire arrivals) (Martell 2001). Preparedness in Alberta is based on an 80% coverage objective (i.e. 80% of the forest area with forecasted Head Fire Intensity values (kW/m) greater than 10, must be reached by aerial or ground resources before a theoretical wildfire exceeds 2.0 ha in size) (Government of Alberta 2018b). Despite the planned rapid deployment of available resources using this consistent and objective approach, IA and BH escapes occur because very high to extreme environmental conditions support rapid wildfire growth and/or surges in wildfire arrival, or because the coverage objective of 80% is too broad resulting in IA resources being spread too thin.

Fine fuel moisture and wind are the main variables contributing to large wildfire growth in the spring. One or two days of drying is sufficient to support rapid wildfire growth if accompanied by strong to extreme winds. IA and BH escapes are surrogate metrics of the environment and/or resource states (i.e. assignable cause). However, similar to control charts, surveillance charts do not assign the specifically contributing cause of the process being out of control.

IA has the highest return on investment and is an immediate indicator of the wildfire and resource environments. However, we consider BH escapes as a stronger process control metric to provide situational awareness compared to IA escapes. If a wildfire cannot be contained by 1000 h the day following when the wildfire was assessed, the wildfire management effort transitions from IA to sustained attack. This phase usually demands more resources because the wildfire is typically larger and more intense. As shown in Fig. 3.6, the arrival of IA resources on a wildfire before it reaches 2 ha in size does not ensure BH success.

In Alberta, lightning-caused wildfires are relatively uncommon until the summer season begins. Historically, human activity causes 82% of the wildfires during May. Though further research is required, our analysis suggests that wildfire arrivals caused by human activity often occur in a ramp-up cluster pattern thereby providing early warning of potential increased wildfire activity. This pattern is typically not as evident with lightning-caused wildfire arrivals. As a result, IA and BH escape surveillance to track trends in threshold exceedances does not perform well to warn of sudden large surges of lightning-caused wildfire arrivals as happened in British Columbia in 2017 and 2018.

We foresee wildfire management duty officers having access to various statistical visualization charts to provide real-time wildfire surveillance of multiple metrics. These charts can provide evidence to support fire bans and area closures. Although we used monthly thresholds for the entire Province, these thresholds can be calculated and applied to administrative areas and ecoregions. Scotto et al. (2014) for example, characterized extreme daily area burned data and variability between districts in Portugal using a clustering analysis that combined the POT method and classification techniques. Shorter analysis time periods can also be used.

Wildfire management duty officers have considerable information to process. This includes what is happening on the entire landscape. The 2017 spring wildfire season was for example, quiet (Fig. 3.11) but in the previous year Alberta experienced a devastating wildfire season when the Horse River Wildfire (MWF009–2016) started on May 1 and a few days later burned into Fort

McMurray. A very strong El Niño event occurred in the 2015/16 winter and continued into the spring. Eight wildfires occurred in the Fort McMurray Forest Area before the Horse River Wildfire started. Three of the four wildfires reported within the Regional Municipality of Wood Buffalo occurred within the Fort McMurray Urban Service Area. Municipal wildfire MMD002–2016 on April 29 challenged firefighting resources from both the Fort McMurray Fire Department and Alberta Wildfire. This wildfire in particular was an early warning of the potential wildfire behaviour. Municipal wildfires are not entered in FIRES unless resources are requested from Alberta Wildfire. This incident highlights the importance of using all wildfires for surveillance and situational awareness. It also showed how even one BH escape spring wildfire can challenge a wildfire management agency and cause a disaster. This is unlike biosurveillance where single influenza occurrences do not trigger a disaster.

Discrete extreme-value modeling for wildfire surveillance using IA and BH escape data is particularly challenging. There is little literature on the application of standard EVT for discrete extreme-value modeling. Anderson (1997) suggested that the maxima of Poisson counts can be reasonably estimated by using the generalized extreme value distribution conditional on having a large enough mean. Our means however are too small due to zero-inflation. We note that a discrete analogue of the generalized Pareto distribution (D-GPD) and the generalized Zipf distribution (GZD) proposed by Hitz et al. (2017) has been found to perform well to estimate discrete extremes. Prieto et al. (2014) used D-GPD to model road accidents in Spain.
Despite the GPD not being a discrete distribution it reportedly performed well to estimate the probability of extreme events including extreme tornado outbreaks (Hitz et al. 2017). We therefore chose to use the Peak-over-threshold (POT) Generalized Pareto Distribution (GPD) to characterize our IA and BH escape data.

There is no standard method of threshold selection when using the POT approach. Lang et al. (1999) provided an overview of the methods and challenges for modeling the POT process. We chose the percentile and Kurtosis methods because they are relatively objective, simple in their application, and Wildfire Management Branch in Alberta uses percentiles as part of a fire weather analysis toolkit in their FIRES system.

If the threshold is too high, the variance increases because of the lower number of exceedances. Likewise, if the threshold is too low, the GPD approximation is not accurate because too many non-extreme values induce bias. An automated selection method to estimate an optimum threshold as proposed by (Bader et al. 2018) may be the best approach to find a balance.
The very strong ENSO warm period in 2015/2016 contributed to the spring drought. The previous very strong ENSO warm period in 1997/1998 was also followed by a disastrous wildfire season in Alberta. A disastrous wildfire season did not follow the very strong ENSO warm period in 1982/1983. After three consecutive wildfire seasons with large areas burned in 1980, 1981 and 1982, Alberta implemented a new preparedness system which combined with fewer reported wildfire starts may have prevented a disastrous wildfire season in 1983. Although disastrous spring wildfire seasons are not dependent on an El Niño occurrence, these warming events contribute to drier wildfire environment conditions. Local conditions however may vary.

Wildfires require three main ingredients: available fuel, ignition (human and lightning), and favourable weather conditions. Since there can be high spatial and temporal variability of weather and subsequent burning conditions it is difficult to identify local teleconnections (i.e. a specific location and short time period). We used December SST anomalies as a simple indicator of the potential persistence of spring wildfire activity. There are a suite of Northern Hemisphere teleconnection indices such as the Arctic Oscillation (AO) Index, Pacific Decadal Oscillation (PDO) Index, Pacific-North American (PNA) Index, and the Oceanic Niño (ONI) Index (National Oceanic and Atmospheric Administration 2018) that can be tracked individually or in combination. Wang et al. (2014) for example, forecasted regional drought-flood changes based on the combined effect of ENSO and PDO.

3.7. Conclusion

We applied simple and operationally viable statistical approaches with visualization techniques commonly used in health sciences to enhance situational awareness of spring wildfire activity in Alberta. We suggest the Wildfire Management Branch implement IA and BH escape surveillance using the daily and 3–day rolling sum May IA escape thresholds of 3 and 10 respectively (kurtosis method), and the 3–day rolling sum May BH escape threshold (97 percentile) of 13.

Our exploratory data analysis and use of IA and BH escape surveillance charts with thresholds focused on the spring season but can be applied during the entire wildfire season, and for all phases of the wildfire cycle (Fig. 3.4). When surveillance charts with multiple statistical thresholds are used with 10 – 14 day outlooks of wildfire occurrence and behaviour potential they can provide early warning of likely wildfire events by indicating the trend direction of IA and BH escapes. It is important to integrate nowcasting with forecasting because it can take two weeks to mobilize resources from outside Canada. Wildfire management agencies can also conduct early surveillance of ENSO data to provide a warning of wildfire environment conditions that are likely to persist in the spring. For example, the surveillance of BH escapes in April can be used to help plan for May, particularly during ENSO warming events, and when extended periods of drying are forecasted. Since every El Niño event is different (timing, length and strength), it is important to track them, particularly the very strong and strong ENSO warming events. Monthly SST anomalies can be tracked using the thresholds identified in Fig. 3.8.

The syndromic surveillance of near-real time IA and BH escapes when combined with CFFDRS and fire occurrence outputs allows wildfire management agencies the opportunity to consider mobilizing resources and activating prevention measures such as fire bans and area closures, in advance. Future work is required to investigate the use of other metrics including fire load and rate of IA and BH escapes, and the use of POT modelling with multivariate generalized Pareto distributions. Temporal and spatial multivariate thresholds can then, for example, be set based on escape rate, fire load and time period. Fire load was an important actor during the 2011 spring wildfire season. From May 11 – 15, 22 on-going fires and 189 new wildfire starts occurred. An early fire load surge on May 1 was an early warning of the potential wildfire activity the following week.

Wildfire disasters in Canada and globally are increasing. Wildfire managers therefore need the best available information and tools to support decision making. This requires innovative and integrated approaches to manage a future world with more wildfire. In particular, the application of advanced statistical approaches are desirable, but this necessitates the engagement and contribution from the statistical sciences community. This horizontal collaboration will help to inform how wildfire management agencies can be better prepared to manage wildfire events.

3.8 Acknowledgements

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4. Characterization of initial fire weather conditions for large spring wildfires in Alberta, Canada

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4.1 Abstract

We evaluated surface and upper synoptic weather patterns, and fire weather indices from the Canadian Forest Fire Danger Rating System for 80 large wildfires during the 1990 – 2019 period in Alberta that started in May and grew to over 1,000 ha. Spread days were identified during the first four days of wildfire activity. We observed two distinct synoptic weather patterns on these days. Pre-frontal and frontal passage activity was the predominant feature associated with 48% of the calendar spread days. Strong south-southeast winds from a surface high centered east of Alberta (west of Hudson Bay) and supported by an upper ridge, and a surface low located southwest of the ridge occurred on 26% of the calendar spread days. Surface analysis indicates the spring wildfire season in Alberta is driven by very high to extreme Initial Spread Index (ISI), a rating of the expected wildfire rate of spread based on Fine Fuel Moisture (FFMC) and wind. Very high to extreme values of Buildup Index (BUI), a rating of the amount of fuel available for consumption, are not a prerequisite for large wildfires in May. For Alberta, this means large wildfires in May can occur after only a few days of dry, windy weather. May wildfire starts account for 23% of all wildfires but are responsible for 55% of the total area burned.

4.2 Introduction

Very large wildfires are a common feature of the boreal fire regime in Canada (Tymstra 2015; Hanes et al. 2019). However, since 1959 Canada has experienced an increase in the number of lightning wildfires (Coogan et al. 2019), area burned (Hanes et al. 2019), and the number of wildfire disasters causing evacuations and structural losses (Tymstra et al. 2019a). Recent disastrous wildfire seasons in western Canada occurred in 2011 (Alberta), 2014 (Northwest Territories), 2015 (Alberta and Saskatchewan), 2016 (Alberta), 2017 and 2018 (British

Columbia), and 2019 (Alberta). Projected higher temperatures, more lightning and weather extremes (Coogan et al. 2019; Flannigan et al. 2009) will contribute to increasing wildfire intensities in the future, and diminishing returns on investment from suppression efforts (Wotton et al. 2017). During the 2005 – 2014 period, extreme wildfire risk increased an estimated 150% to 600% in the last decade (2005 – 2014) in western Canada as a result of the combined impact of anthropogenic and natural forcing compared to natural variability alone (Kirchmeier-Young et al. 2017).

Climate change impacts also include changes in spring phenology resulting in earlier spring wildfire seasons (Beaubien and Hamann 2011; Pickell et al. 2017). Spring wildfires across Canada are particularly a challenge during the period between snowmelt and green-up when suppression resources may not yet be fully available, and low fuel moisture levels contribute to extreme wildfire behavior. In Alberta, spring is the critical season (Tymstra et al. 2019b) when nearly all of the associated structural losses occur from wildfires. There is therefore great interest in understanding the environmental conditions contributing to wildfires that start in spring, subsequently grow large and become challenging to manage.

Various multivariate approaches have been used to investigate biophysical factors associated with wildfires (occurrence and area burned) in, for example, France (Ganteaume and Jappiot 2013); Spain (Verdú et al. 2012; Viedma et al. 2015), Portugal (Parente et al. 2016), United States (Parks et al. 2018), and in Canada (Cumming 2001, Krawchuk et al. 2006).

In their investigation of the relationship of various meteorological variables to area burned in Canada, Flannigan and Harrington (1988) found the strongest predictor of the variance in area burned was the duration of dry periods (< 1.5 mm precipitation). Earlier studies recognized the importance of wind; Byram (1954) suggesting certain wind profiles associated with blowup wildfires, and Schaefer (1957) linking jet streams and wildfires.

Schroeder et al. (1964) identified critical synoptic weather types associated with periods of extreme fire behavior, and Brotak and Reifsnyder (1977) extended similar weather analysis to investigate 60 major wildfires in the eastern United States. Frontal passages were a common factor for 45 of these wildfires. Skinner et al. (2002) found an association between large areas burned in western Canada with 500 hPa ridging, and the mean 500 hPa height difference between 45° N and 65° N longitude. In Alberta, frontal passages are often associated with the breakdown of these 500 hPa ridges and the subsequent arrival of lightning-caused wildfires (Nimchuk 1983).

These early studies highlight the importance of understanding synoptic weather patterns associated with critical wildfire activity, and the need to be better prepared by predicting when these patterns develop. The upper 500 hPa chart is an important wildfire behavior forecasting product because the weather conditions at this mid-troposphere height (altitude of approximately 5500 m), influence the development and movement of surface weather systems. For example, surface low pressure systems tend to track the 500 hPa wind flow which usually follows the height contours. Fire behavior analysts therefore need to understand how forecasted changes in the 500 hPa weather pattern relative to the location of an active wildfire may impact the behavior of that wildfire in the future.

More recent studies have applied statistical approaches for synoptic weather typing using interpolated geospatial gridded data from meteorological observations or modelled reanalysis products and then correlating these with fire danger metrics. Examples include the use of composite map analysis using NCEP/NCAR reanalysis outputs of days with highest area burned (Pereira et al. 2005), correlation analysis of NCEP/NCAR reanalysis outputs and the Haines Index and Palmer Drought Index (Trouet et al. 2009), fuzzy c-means cluster analysis classification of fire days into synoptic weather groups (Duane and Brotons 2018); k-means cluster analysis classification of weather type (Ruffault et al. 2016); and Self-Organized Map classification of synoptic weather patterns associated with critical fire weather conditions (Crimmins 2006; Lagerquist et al. 2017; Zhong et al. 2020).

We similarly investigate the association between meteorological variables and synoptic conditions but focus on May wildfire activity in the Province of Alberta, Canada. Our attention to the month of May is motivated not only by recent disastrous spring seasons but also past events such as the “Seven Days in May” wildfire outbreak in 1968 (McLean and Coulcher 1968) when a persistent blocking pattern aloft allowed a surface high to sustain strong and dry south and southeast winds over central Alberta (Fig. 4.1).

The study area is depicted in Fig. 4.2. Only those wildfires within the boreal forest in Alberta during the 1990 – 2019 period were included in the study. This period was selected because detailed wildfire report and weather data in the Fire Information and Resource Environment System (FIRES) which is managed by Alberta's Wildfire Management Branch (WMB), begins in 1990. The WMB is responsible for managing wildfires on provincial forested lands. Wildfires in the national parks are managed separately and were excluded because of the absence of detailed daily wildfire data similar to that available in Alberta. Wildfire report data from FIRES are available publically (https://wildfire.alberta.ca/respources/), and weather data are available via a request to the WMB. The next section describes the data and analysis methods used to

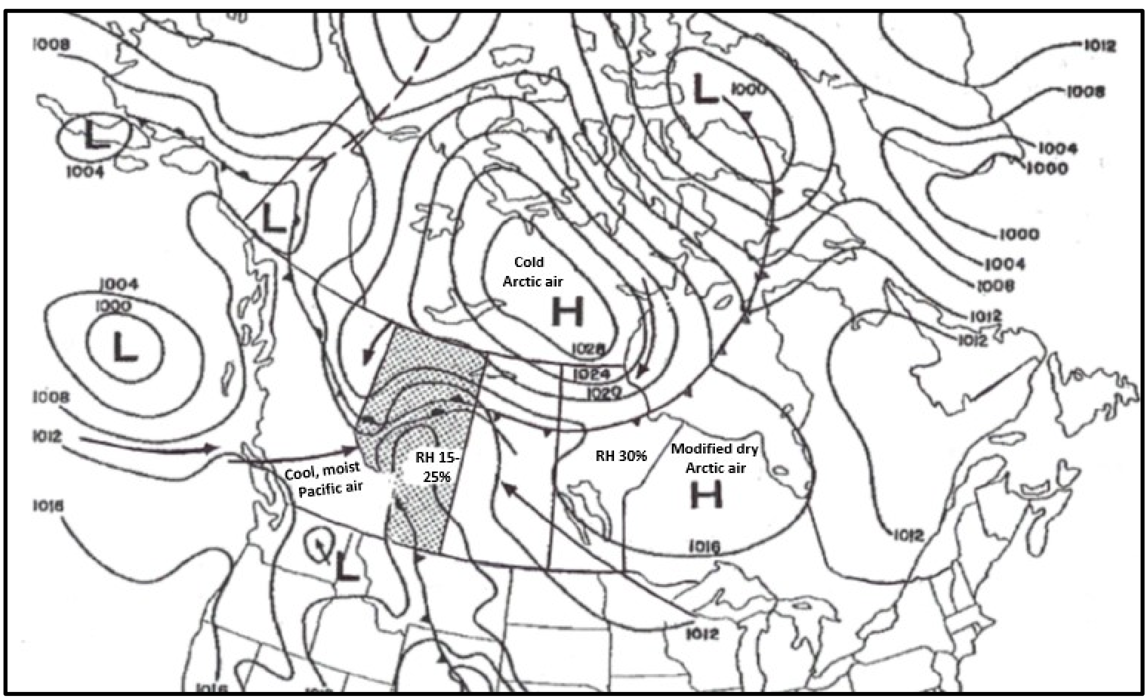

Figure 4.1. Surface weather analysis May 23, 1968 1300 h MST (2000 h GMT). Note the location of the high pressure area west of Hudson Bay that resulted in a strong, dry, southeast anti-cyclonic flow over central Alberta, and the low pressure area west of the province with a cyclonic flow supporting the southeast flow. Modified from Kiil and Grigel (1969).

characterize the fire weather conditions of large spring wildfires in May. This is followed by the results and discussion sections. Our discussion focuses on the operational implications for wildfire behavior analysts working on incident management teams. The conclusion summarizes the key results, limitations and research gaps, and opportunities for enhanced wildfire preparedness in the spring.

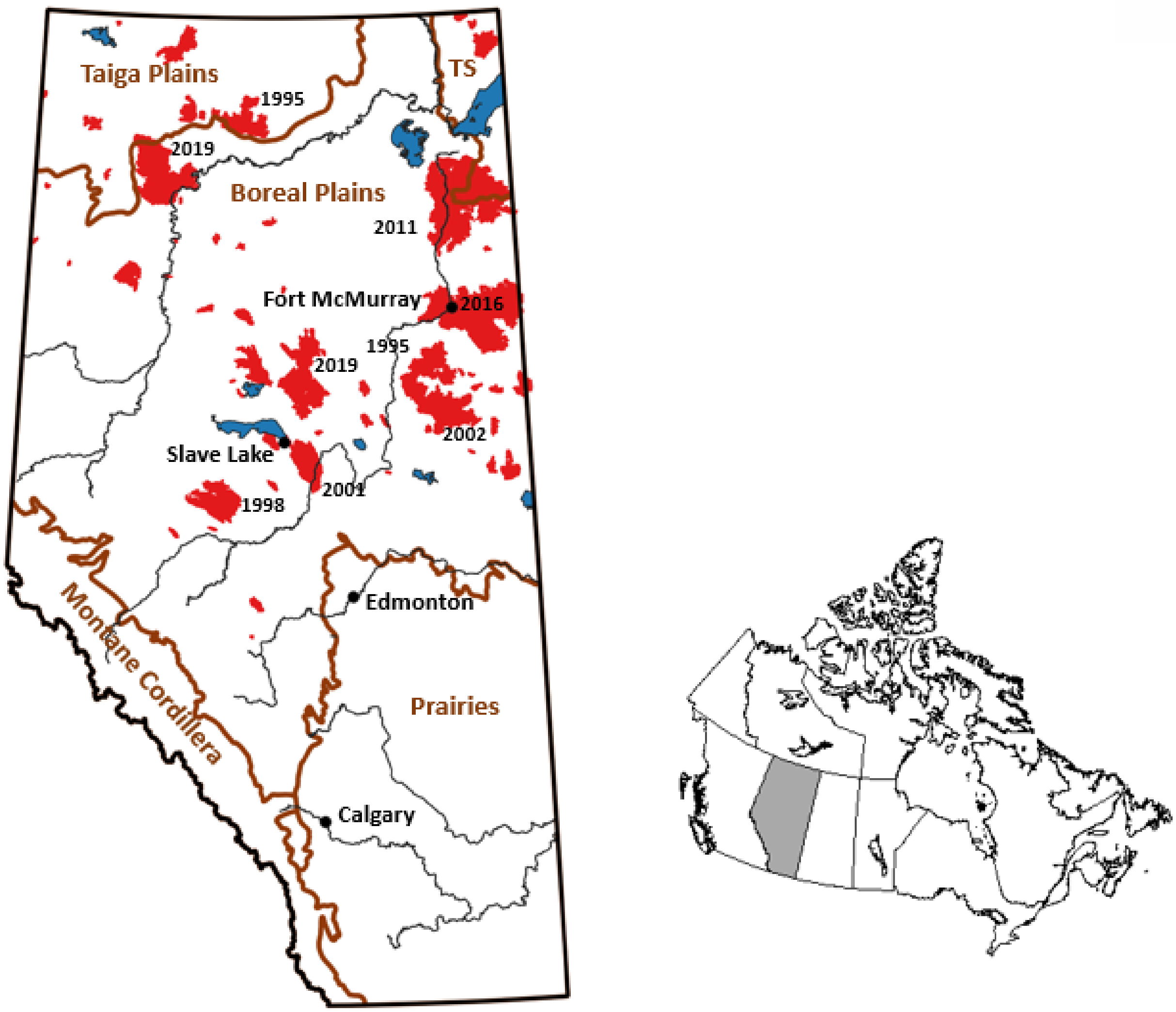

Figure 4.2. Location of the Province of Alberta and wildfires greater than 1,000 ha in size on provincial forested lands that started during the month of May during the 1990 – 2019 period. Wildfires greater than 100,000 ha are labelled by year. The five ecozones are delineated and labelled. TS = Taiga Shield Ecozone. Wildfire perimeter data provided by the Wildfire Management Branch, Edmonton, Alberta.

4.3 Study Area

Alberta is the sixth largest province of Canada, landlocked by British Columbia to the west, Saskatchewan to the east, Northwest Territories to the north, and the state of Montana, USA (not included in Fig. 4.2) to the south. There are five ecozones in Alberta: Prairies, Montane Cordillera, Boreal Plains, Taiga Plains and Taiga Shield (Wiken 1986). The Boreal Plains Ecozone covers most of Alberta's forested landscape and extends east into Saskatchewan and Manitoba. The Boreal Plains Ecozone is primarily a forested landscape of white (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) BSP), balsam fir (*Abies balsamea* (L.) Mill.), jack pine (*Pinus banksiana* Lamb.), aspen (*Populous treminoides* Michx.), poplar (*Populous balsamifera* L.) and birch (*Betula paperifera* Marsh.), interspersed with peatlands (bogs, fens and swamps). This ecozone has the highest total incidence of wildfires and area burned in Alberta. The Taiga Shield Ecozone occurs in the northwest corner of the province and the Taiga Plain extends south into northeast Alberta north of Athabasca Lake.

Alberta's geographic location and topographic features influence weather patterns, which impacts the wildfire season. The Rocky Mountains and foothills traverse northwest from the Canada-United States border (49° N) to near Grande Prairie (55° N). These features support the formation of clouds and precipitation during easterly upslope wind flows, and warming and drying during westerly downslope wind flows. North of Grande Cache, moist Pacific air masses have relatively easy entry into central and northern Alberta. During spring, air masses originating from the Arctic also move unimpeded as they travel south and southeast into the Prairie Provinces (Alberta, Saskatchewan and Manitoba).

4.4 Methods

For the 1990 – 2019 period all May wildfire starts in Alberta were selected with a reported extinguished size exceeding 1,000 ha in size (Fig. 4.2). Point attribute and perimeter data were obtained from the Alberta Wildfire Management Branch in Edmonton, Alberta. This size threshold was selected because wildfires that reach 1,000 ha or greater in size usually become complex incidents requiring large amounts of equipment and firefighters. Point attribute and perimeter data were obtained from the Alberta Wildfire Management Branch in Edmonton, Alberta. If a wildfire in Alberta grows larger than 2.0 ha before initial attack begins it is considered an initial attack (IA) escape. If a wildfire cannot be contained by 1000 h on the following day when it was assessed, it is reported as a containment or Being Held (BH) escape. Of the selected 80 wildfires, 57 escaped both IA and BH, and 4 escaped IA but had BH success. Despite initial attack resources arriving successfully 19 wildfires before they exceeded 2 ha in size, BH success was attained on only one wildfire.

Most wildfires are assessed the day they are reported which typically is the day they started. We focus on the first four days, which includes the wildfire start date. We consider the first four days as the critical initial suppression phase. For the three wildfires starting earlier but discovered and reported later (referred to as holdover), and the three wildfires with start dates reported as unknown, we used the discovered date as day one. Podur and Wotton (2011) used an ISI classification threshold of ≥ 8.7 to differentiate wildfire spread days from non–spread days. ISI is a numerical rating of a wildfire's spread potential (Van Wagner 1987). To derive spread day distributions for input into burn probability modeling, Parisien et al. (2012) applied a calculated rate of spread threshold of ≥ 1 m min^{-1} to identify spread days. We chose a mixed approach to identify a spread day event. A spread day occurred on day 1 if the reported wildfire size exceeded 200 ha or the noon ISI was 9 or greater. Spread days occurred on days 2 to 4, if either they doubled in size from the previous day or the ISI ≥ 9 threshold was reached. The ISI threshold of 9 is the start of the very high ISI category used in Alberta (Table 4.1). Days with a reported wildfire status as BH or UC (under control) were not considered as spread days.

We analyzed surface (3-hour intervals) and 500 hPa (2x/day) synoptic weather patterns for the first four days for all 80 wildfires. For those days when a spread event occurred, we manually characterized the weather patterns into 24 surface and upper weather pattern combinations (see Table 4.2 in Results). Ridges and troughs were identified as elongated areas of high (ridge) or low (trough) pressure occurring at the surface or aloft. We identified air masses that were more concentric in shape as lows or highs. The weather pattern "other" includes col (neutral) and zonal flow.

Table 4.1. Hazard rating classes for fire weather index codes and indices used in Alberta. FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Buildup Index, and FWI = Fire Weather Index.

Hazard Rating	FFMC	DMC	DC	ISI	BUI	FWI
Low	0-76	0-21	0-79	0-1.5	0-24	0-4.5
Moderate	77-84	22-27	80-189	2-4	25-40	4.5-10.5
High	85-88	28-40	190-299	5-8	41-60	10.5-18.5
Very High	89-91	41-60	300-424	9-15	61-89	18.5-29.5
Extreme	92+	61+	425+	16+	90+	29.5+

For the 1990 – 2004 period, we accessed surface maps from the National Oceanic and Administration (NOAA) National Centers for Environmental Prediction (NCEP) surface analysis archive (National Oceanic and Atmospheric Administration 2021a), and 500 hPa maps from the NOAA Central Library weather and climate collections (National Oceanic and Atmospheric Administration 2021b). To address gaps in the surface maps during the 1990 – 2004 period we also accessed the daily surface weather maps from the NOAA central library weather and climate collections (National Oceanic and Atmospheric Administration 2021c).

For the 2005 – 2019 period, we accessed surface maps from the NOAA NCEP surface analysis archives (National Oceanic and Atmospheric Administration 2021c), and 500 hPa maps from the NOAA NCEP daily weather map archives (National Oceanic and Atmospheric Administration 2021d)

We used the McElhinny et al. (2020) global high-resolution (0.25° x 0.25°) data set of FWI System fuel moisture codes and fire behavior indices that were calculated using surface meteorology data from the ERA5 reanalysis for 1979 – 2018 period. For our study, we extended this data set to include 2019. The Province of Alberta including an edge buffer was clipped from the global data set between -120.125° and -109.875° longitude and 48.875° and 60.125° latitude. FWI System outputs were calculated using the ERA5 deterministic meteorology outputs of temperature (° C), dewpoint temperature (° C) used to derive relative humidity (%), wind speed (km/h), and 24–hour accumulated precipitation (mm). The standard overwinter Drought Code adjustment was used to derive starting values as described by McElhinny et al. (2020).

The FWI system was developed adhering to the World Meteorological Organization reporting standards (Lawson and Armitage 2008). For forecasting purposes, the recommended hourly surface wind speed for use in the FWI system is the average 10–m wind speed over the last 10 minutes before the hour. In Alberta, this average wind speed is calculated using sampling frequency of 4 Hz (every 0.25 seconds). Maximum (peak) observed wind speed within the last hour were obtained from the nearest weather station. Peak wind speeds continuing longer than 1

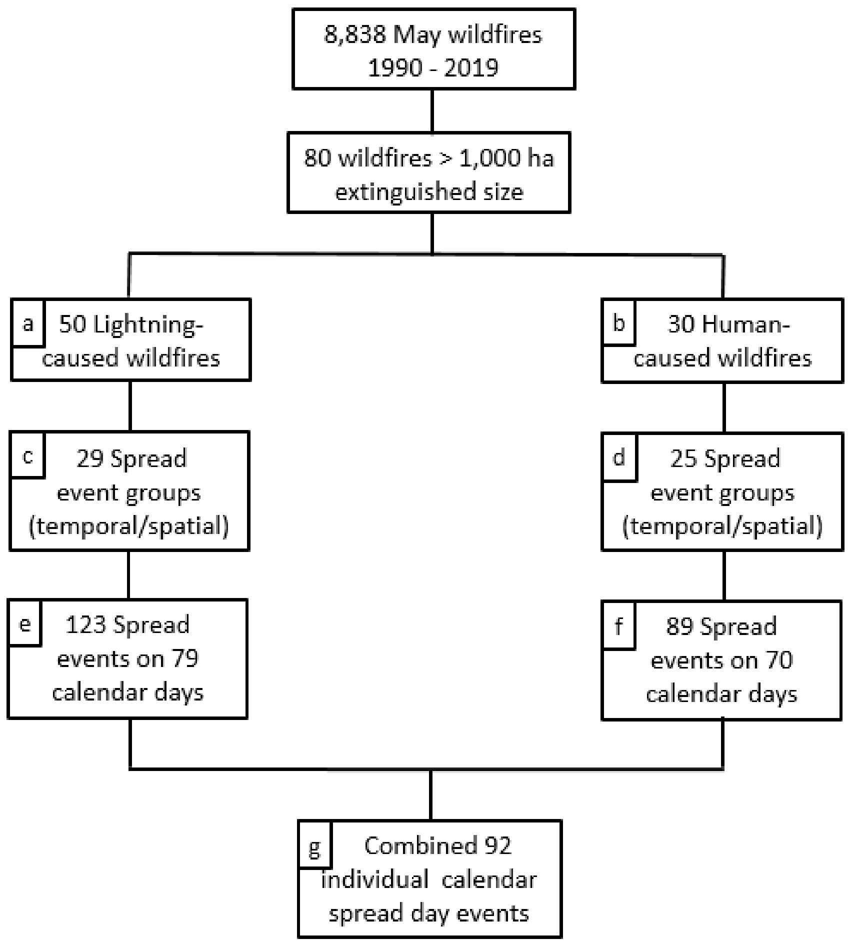

Figure 4.3. Calendar day spread event flowchart. The 80 large wildfires are first categorized by cause (boxes a and b) and then grouped into spatial–temporal spread event groups (boxes c and d). The total number of spread events are shown in boxes e and f. The combined number of individual calendar days with one or more spread events is shown in box g.

minute can significantly impact fire behavior (Crosby and Chandler 2004), but they are not an input in the calculation of the Fine Fuel Moisture Code (FFMC) and ISI. FFMC is a numerical rating of the moisture content of fine fuels and their ease of ignition and flammability (Van Wagner 1987). If gusts are reported, fire behavior analysts typically increase the input wind speed to calibrate their forecast to match what is observed.

If gusts were reported from the nearest weather station, we converted the 10–minute average wind speed was converted to a probable maximum 1–minute average wind speed and recalculated the FFMC and ISI values using the adjusted wind speed. The wind speeds were adjusted using a piecewise linear function to approximate the converted metric values of the tabular data published by Crosby and Chandler (2004).

For $WS_{10} < 19$, $WS_1 = (1.505954 * WS_{10}) * 1.11$
For $WS_{10} \geq 19$, $WS_1 = (WS_{10} + 8) * 1.11$

where, WS_1 = adjusted wind speed, and WS_{10} = 10-minute average wind speed (km/h).

Spread events were spatially and temporally grouped into 29 lightning–caused and 25 human–caused spread event groups (Fig. 4.3 boxes c and d). A 100 km radius centered on the ignition points of lightning–caused wildfires, and a 50 km radius centered on the human–caused wildfire ignition points were used to maximize the grouping of wildfires based on similar start dates and locations. The larger radius for lightning–caused wildfires allowed for the inclusion of wildfires with the same start dates and orientation with a cold front passage. The use of spread day event groups facilitated the qualitative analysis of the synoptic weather types associated with the wildfire spread events.

The 54 groups yielded a total of 212 spread events (box e + box f in Fig. 4.3). Many of the spread events within a group had multiple wildfires occurring on the same day. For example, spread event group 3 (see Appendix B Table B1) included 5 wildfires with 15 spread events occurring on 5 separate calendar days. The 212 spread events occurred on 92 individual (unique) calendar day spread events (box g in Fig. 4.3).

We not only investigated the occurrence of synoptic weather patterns during the identified spread event days similar to the 1968 wildfire outbreak, but also during non-wildfire days. If synoptic weather patterns 4a and 4c (Table 4.2) with south-southeast winds exceeding 18.5 km/h (10 knots or full barb wind speed symbol on weather maps) occurred, it was considered as a potential critical spread day similar to the 1968 wildfire event. The Town of Slave Lake was used as a central reference location to cross–validate the wind flow assessed from the surface weather maps using historical hourly weather data for the Slave Lake airport obtained from the Government of Canada historical hourly weather data (Government of Canada 2021).

We selected the two human–caused wildfires with the highest community impact (structural loss) as representative examples of the synoptic patterns that supported the extreme wildfire behavior observed on these wildfires. The 2011 Slave Lake Wildfire (SWF065–2011) is an example of a surface and upper ridging synoptic weather event, and the 2016 Fort McMurray Wildfire (MWF009–2016) is an example of a frontal passage synoptic weather event. These two wildfires are paired with two additional examples (Wildfire HWF070–2012 on May 26, 2012, and Wildfire PWF019–2008 on May 17, 2008) with similar synoptic weather patterns.

Data analysis, including graphics and reported statistical tests, were completed using the R software environment (R Core Team 2020, Python programming language (Python Software Foundation 2021), and the Cartopy Python Package (Met Office 2021).

4.5 Results

4.5.1 Wildfire Cause, Area Burned, and Synoptic Weather Patterns

Table 4.2 summarizes the synoptic scale weather patterns and associated pre-frontal, frontal passage and gust occurrences for the 149 spread day events (79 lightning and 70 human–caused) during the 1990 – 2019 period. The two most frequent weather patterns when wildfire spread days occurred are Pattern 1: surface trough or low with an upper ridge or high (41%), and Pattern 4: surface ridge or high with an upper ridge or high (36%), as shown in Table 2. Of the spread days associated with a surface trough or low and an upper ridge or high, 70% were due to lightning-caused wildfires. This is due to the higher occurrence of frontal activity which causes warm air ahead of the advancing cold front to rise and develop cumulus or cumulonimbus clouds and thunderstorms. In comparison, of the spread days associated with a surface ridge or

Table 4.2. Synoptic scale weather patterns and associated pre–frontal, frontal passage and gust occurrences for the 149 spread day events associated with one or more wildfires. For example, a total of 26 spread day events occurred with weather pattern 1a (trough at the surface and a ridge at 500 hPa), 4 days had pre-frontal activity (3 with reported gusts), 8 days had frontal passage (7 with reported gusts), and 11 days had gusts but with no pre-frontal or frontal passage activity.

Synoptic Scale Weather Pattern	Surface + Upper (500mb) Weather Pattern	Number of Spread Day Events			
		Total	Pre-Frontal/ Gusts	Frontal Passage/Gusts	Gusts
Trough/Low + Ridge/High	1a: Trough + Ridge	26	4/3	8/7	11
	1b: Trough + High	1	0	1/1	0
	1c: Low + Ridge	32	2/1	17/8	9
	1d: Low + High	2	0	0	0
Trough/Low + Trough/Low	2a: Trough + Trough	5	0	4/1	0
	2b: Trough + Low	3	0	1/1	1
	2c: Low + Trough	1	0	1/1	0
	2d: Low + Low	1	0	0	0
Trough/Low + Other	3a: Trough + Col	5	0	0	3
	3b: Trough + Zonal Flow	1	0	0	1
	3c: Low + Other	1	0	0	1
Ridge/High + Ridge/High	4a: Ridge + Ridge	12	1/1	2/2	6
	4b: Ridge + High	0	0	0	0
	4c: High + Ridge	40	5/2	6/3	18
	4d: High + High	2	0	0	2
Ridge/High + Trough/Low	5a: Ridge + Trough	0	0	0	0
	5b: Ridge + Low	0	0	0	0
	5c: High + Trough	4	0	2/2	1
	5d: High + Low	2	0	2/0	0
Ridge/High + Other	6a: Ridge + Col	1	0	1/0	0
	6b: High + Zonal Flow	4	0	0	3
	6c: High + Col	2	0	1/1	0
Other + Ridge	7a: Col + Ridge	3	0	1/1	0
Other + Other	8a: Col + Col	1	0	0	1

high, and an upper ridge or high, 67% were due to human-caused wildfires. The 149 spread day events fall on 92 individual calendar days (i.e. with one of more wildfires).

Simplified surface and 500 hPa synoptic weather maps were created for illustrative purposes using ERA5 model output. Representative examples of synoptic weather patterns 4a and 4c (Table 4.2) are shown in Fig. 4.4 The merging of a cyclonic flow with an anti-cyclonic flow results in a south-southeast wind flow over central and eastern Alberta. These surface patterns are supported by an upper ridge aloft (500 hPa) blocking moist Pacific air masses from entering

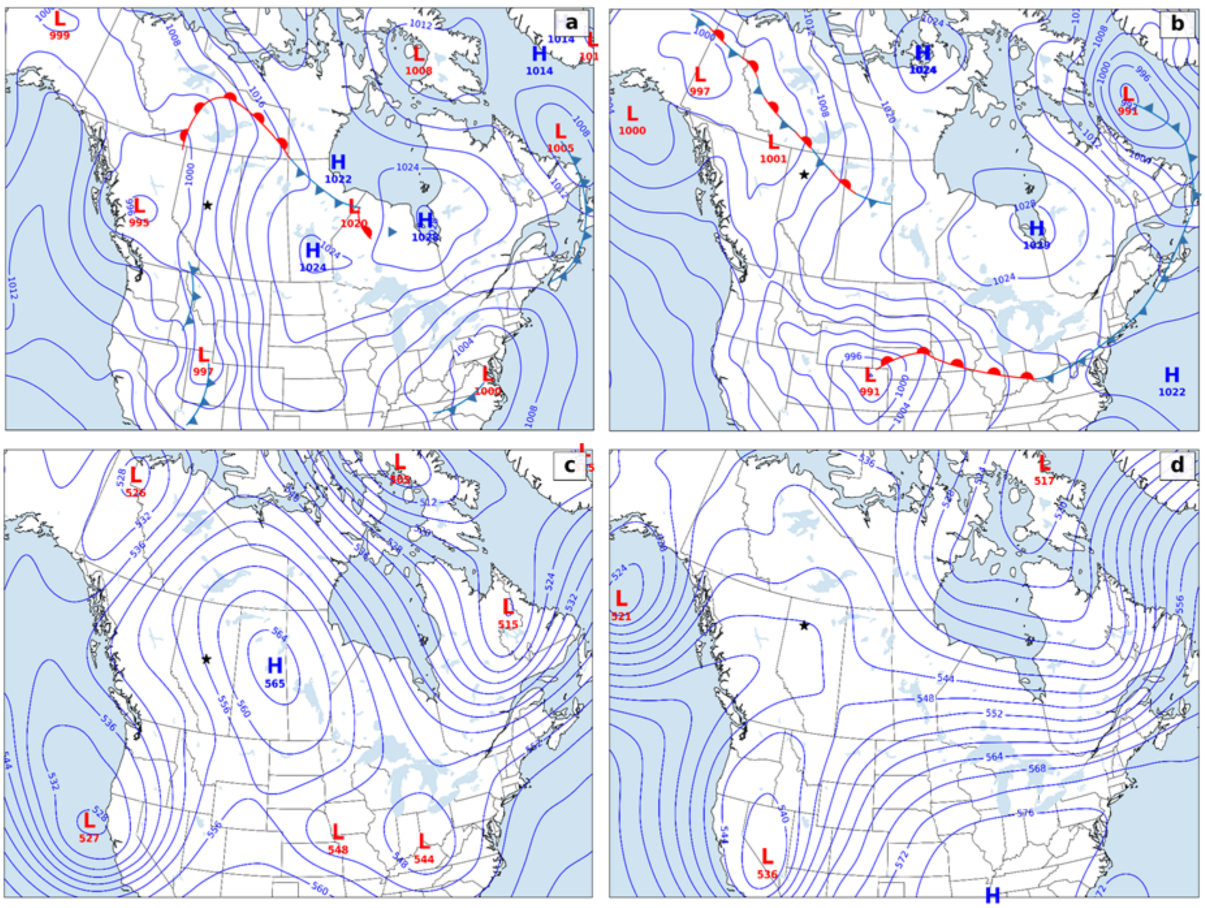

Fig. 4.4. **S**urface and 500 hPa analyses on May 15, 2011 (a = surface map, c = 500 hPa map), and May 26, 2012 (b = surface map, d = 500 hPa map). Surface maps are 1800 h MDT and 500 hPa maps are 0600 h MDT. The black star represents the Town of Slave Lake and Wildfire SWF065-2011 (maps a and c), and Wildfire HWF070–2012 (maps b and d). Wildfire SWF065–011 burned through the Town of Slave Lake on May 15th. Surface and 500 hPa maps are based on ERA5 model output. Fronts are delineated on the surface maps.

Alberta. Little to no lightning occurs with synoptic weather patterns 4a and 4c because of the characteristic stable atmospheric conditions. As well, lightning is strongly seasonal; human–caused wildfires are dominant in April and May because of the low occurrence of lightning.

A continental polar air mass centered west and southwest of Hudson Bay with south-southeast winds over central and eastern Alberta occurred on 10% of all days in May for the 12 years during the 1990 – 2019 period when no large wildfires started in May (Fig. 4.5). The occurrence of this synoptic weather pattern increased to 19% during the other 18 years when large wildfires did start in May. During the 92 individual calendar spread days, the occurrence of a Hudson Bay continental polar air mass with a surface low positioned in or near southwest Alberta occurred on about 26% of those days.

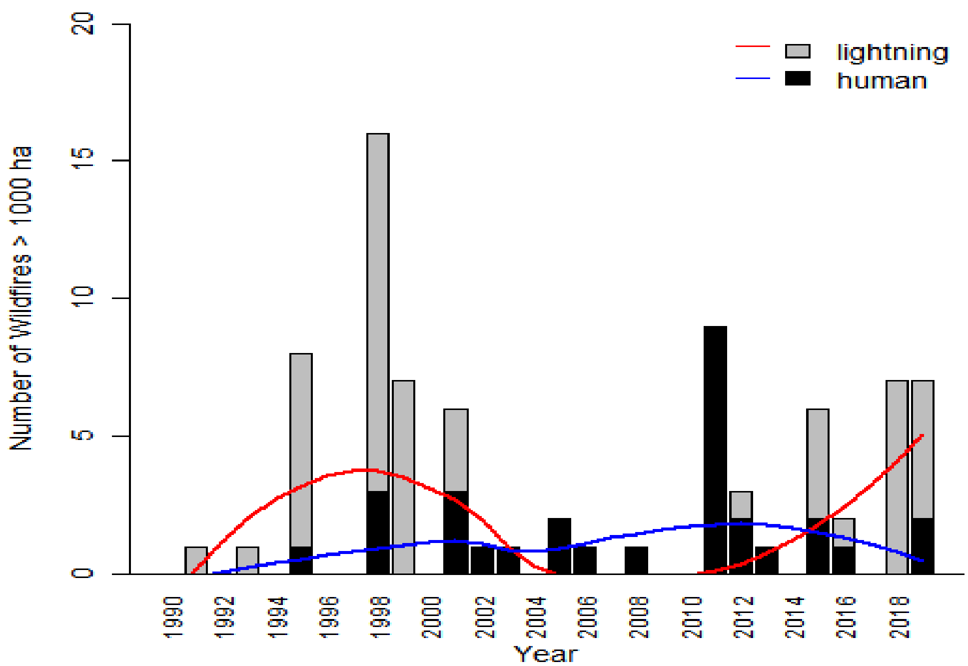

Fig. 4.5 Annual number of lightning and human caused wildfires starting in May and exceeding 1,000 ha in extinguished size for the 1990 – 2019 period. The red and blues are locally weighted smoothing outputs.

Representative examples of synoptic weather patterns 1a and 1c (Table 2.4) are shown in Fig. 4.6. These patterns are associated with cold front passages. On May 2, 2016, an upper ridge was centered over Alberta. At the surface, a north-south oriented cold front positioned along the west coast of British Columbia began tracking eastward on May 3rd. The blocking upper ridge moved east on May 4th allowing the cold front entry into Alberta. At 1200 h MDT the cold front was positioned just west of the Fort McMurray Urban Service Area (Fig. 4.6a). AT 1800 h MDT the cold front was positioned just west of the Fort McMurray Urban Service Area. Strong southwest winds ahead of the cold front pushed the 2016 Horse River Wildfire into Fort McMurray. At 1820 h MDT on May 4th, a mandatory evacuation was declared. A similar synoptic weather pattern occurred on May 17, 2008 when a cold front passed over Wildfire PWF019-2008 (Fig. 4.6b).

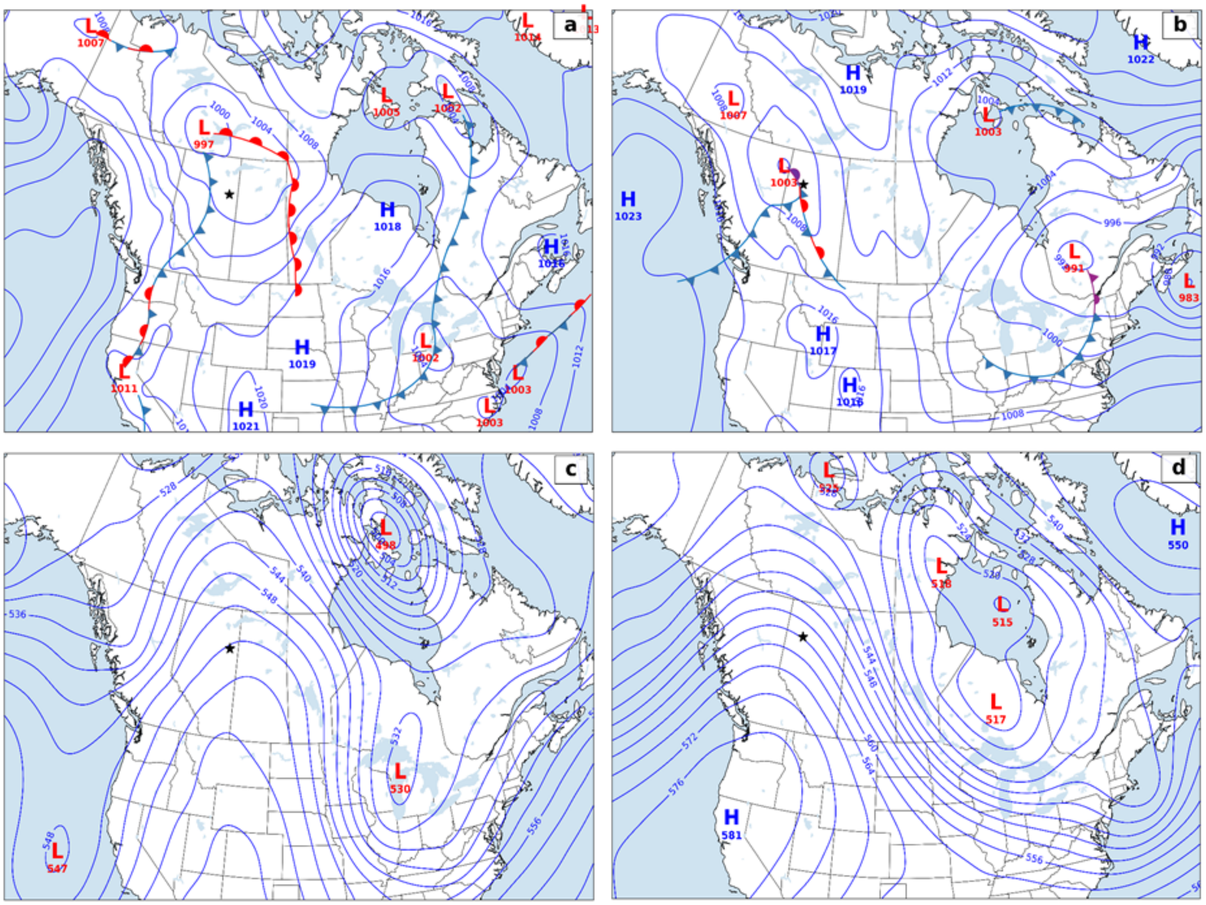

Figure 4.6. Surface and 500 hPa analysis on May 4, 2016 (a = surface map, c = 500 hPa map), and May 17, 2008 (b = surface map, d = 500 hPa map). Surface maps are 1200 h MDT (map a) and 1800 h MDT (map b), and 500 hPa maps are 0600 h MDT. The black star represents the Fort McMurray Urban Service Area (maps a and c), and Wildfire PWF019-2008 (maps b and d). Surface and 500 hPa maps are based on ERA5 model output. Fronts are delineated on the surface maps.

Pre-frontal and/or frontal passage activity occurred on 44 (48%) of the 92 calendar spread days. In Alberta, these events are often associated with the breakdown of a 500 hPa ridge and increased threat of atmospheric conditions (strong winds and atmospheric instability) conducive to extreme wildfire behavior (Nimchuk 1983).

In Alberta, wildfire starts in May accounted for 55% of the total extinguished area of all wildfires during the wildfire season (March 1 – October 30) for the 1990 – 2019 period (Fig. 4.7). For the 80 wildfires that exceeded 1,000 ha in size, approximately 25% of their total extinguished area occurred during the initial four days of wildfire growth.

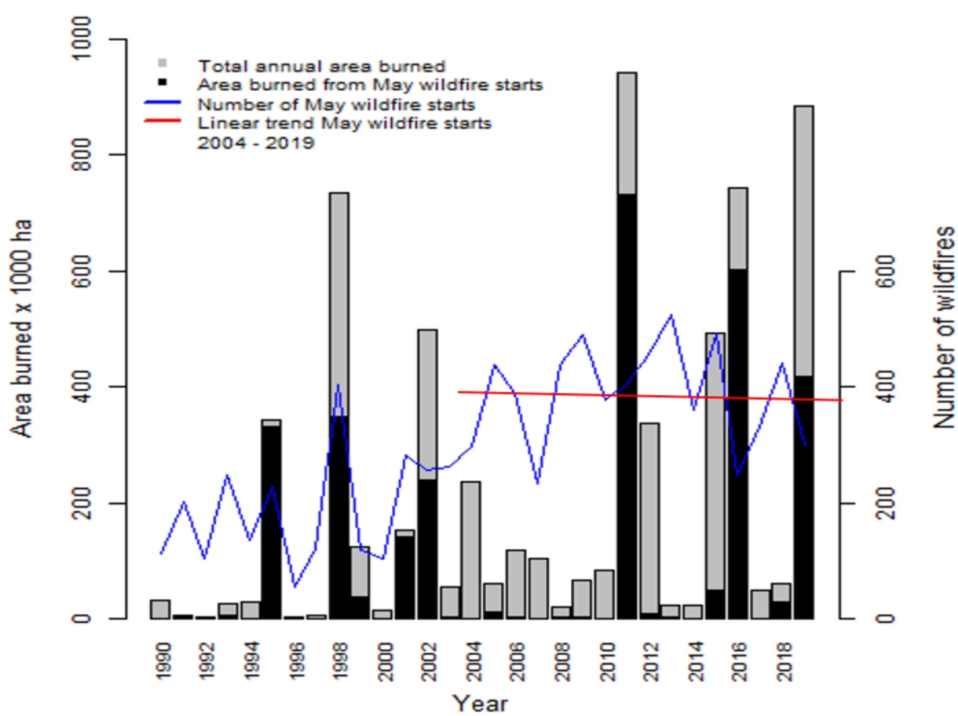

Fig. 4.7. Area burned from May wildfire starts compared to the total annual area burned and number of May wildfire starts with a linear trend line for the period 2004 – 2019 (reporting procedures changed in 2004 resulting in more reported wildfires).

Humans and undetermined causes account for 91% of all May wildfire starts (n= 8838) that exceed 0.1 ha in extinguished size. For wildfires greater than 1,000 ha during the first decade (1990 – 1999), lightning was the dominate cause (88%). In the second decade (2000 – 2009) human activity was the dominate cause (75%). An approximate 50–50 percentage was observed in the last decade, with 94% of the lightning-caused wildfires occurring in the last 5 years (2015 – 2019) (Fig. 4.7).

About 58% and 42% of the spread events (*n* = 212) are associated with lightning- and human-caused wildfires respectively. The frequency of 1-, 2-, 3-, and 4-dayt human- and lightning caused associated spread events is shown in Fig. 4.8. Human-caused wildfires have a higher frequency of 4 spread days compared to lightning-caused wildfires that have a higher frequency of 2 – 3 spread days. There is however, no significant difference in their distributions (K-S test not significant at α= 0.05).

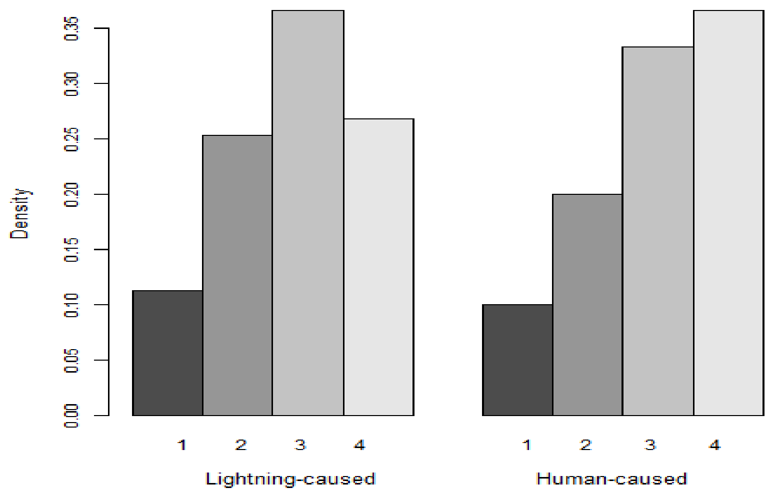

Fig. 4.8. Distribution of 1–, 2–, 3–, and 4–day spread events for human– and lightning–caused wildfires starting in May and exceeding 1,000 ha in size.

4.5.2 Fire Danger Analysis

Table 4.3 summarizes the median (x̃), maximum (max), and bootstrap 95% confidence intervals (CI) for FFMC, ISI and BUI by cause and period for the spread day events. BUI is a numerical rating of the amount of fuel available for consumption which provides an indication of the difficulty to contain a wildfire. The distributions of FFMC, ISI and BUI for all categories in Table 3 except Period 1 (1990 – 2004) and Period 2 (2005 – 2019) for human-caused wildfire spread day events failed the Shapiro-Wilk normality test (α = 0.5). Median values were therefore calculated and a bootstrap approach applied to estimate their 95% CI. If the confidence intervals for the compared medians did not overlap we concluded there was a significant statistical difference between the medians of the two distributions. The paired groups with different medians are highlighted (colored) in Table 4.3.

The median FFMC for all spread day events for the 1990 – 2019 period is very high (91) as shown in Table 4.1. The median ISI is also very high (16.8). The median BUI in comparison is in the high category (48). Therefore, while the spread events are characterized by very high and extreme FFMC and ISI values, very high to extreme BUI is not a prerequisite for large spring wildfires in Alberta. For example, in 2011, BUI values for the daily spread events ranged from 8 – 134. Snow patches were still evident the day before Wildfire SWF065-2011 burned through the Town of Slave Lake. On May 14, the nearby S2 automatic weather station reported a BUI of 20 (low category).

FFMC has narrower categorical ranges (e.g. Very High 89 – 91) compared to ISI and BUI, and is the only FWI index not open-ended. FFMC ranges from 0 – 99 and has a maximum probable value of 96 (de Groot 1987). The maximum value observed for all 212 spread day events was 96.4. FFMC values ≥ 94 were only observed in the second period (2005 – 2019).

As well, these extreme FFMC values only occurred when the relative humidity was very low or extreme (n = 24, $\bar{x}$ RH = 21 %). Significant increases in the mean median FFMC for lightning-, human-, and all-caused wildfires occurred from Period 1 to Period 2. Median ISI increased from Period 1 to Period 2 for lightning-caused wildfires. Human-caused wildfires had a higher median ISI (16.7) compared to lightning-caused wildfires for the entire period (1990 – 2019).

Table 4.4 summarizes the median ($\tilde{x}$), maximum, and bootstrap median confidence intervals (CI) for FFMC, ISI and BUI by cause and period for the non-spread day events (n = 108) during the first four days. The median FFMC for all non-spread day events for the 1990 – 2019 period is high (87). The difference compared to the very high FFMC (91) for the spread day events is statistically significant. The median ISI for the non-spread day events is moderate (4.4) compared to the very high median ISI for the spread day events (13.7). This difference is also statistically significant. The median BUI values for spread (47.5) and non-spread (45) day events are not statistically different. However, the median BUI value is statistically different between Periods 1 and 2 for all causes and lightning–caused alone.

Table 4.3. Median (x̃), maximum (max), and bootstrap confidence intervals (CI) for FFMC, ISI and BUI by cause and period for the spread day events. The paired coloured cells indicate significant differences between the distributions of FFMC, ISI and BUI medians.

Spread Day Events	*n*	FFMC		ISI		BUI	
		x̃ 0.95 CI	Max	x̃ 0.95 CI	max	x̃ 0.95 CI	max
All (1990 – 2019)	212	91 90.0 – 91.0	96.4	13.7 12.5 – 15.2	68.4	47.5 43.5 – 51.5	132
All lightning-caused wildfires (1990 – 2019)	127	91 90.0 – 91.0	95	12.2 11.0 – 13.5	30.3	49 42.0 – 53.0	132
All human-caused (1990 – 2019)	85	92 90.7 – 92	96.4	16.7 14.6 – 22.0	68.4	46 38.0 – 46.0	102
Period 1 (1990 – 2004) All	104	90 88.1 – 90.0	93	13.2 11.2 – 15.1	68.4	41 35.0 – 45.0	92
Period 2 (2005 – 2019) All	108	92.3 91.9 – 93.0	96.4	14.1 12.5 – 15.8	53.7	53 48.0 – 58.5	132
Period 1 (1990 – 2004) lightning-caused	85	90 89.0 – 90.0	93	12.7 10.8 – 14.3	30.3	38 33.0 – 42.0	83
Period 2 (2005 – 2019) lightning-caused	42	92 90.7 – 92.0	95	17.8 14.3 – 25.95	29	84 67.0 – 92.0	132
Period 1 (1990 – 2004) human-caused	19	90 87.0 – 90.0	93	16.6 9.6 – 25.7	68.4	53 35.0 – 58.0	92
Period 2 (2005 – 2019) human-caused	66	92 (0.367) 90.7 – 92.0	96.4	17.8 (2.972) 14.4 – 25.6	53.7	46 (3.155) 29.0 – 49.0	102

Table 4.4. Median (x̃), maximum (max), and bootstrap confidence intervals (CI) for FFMC, ISI and BUI by cause and period for the non-spread day events. The paired coloured cells indicate significant differences between the distributions of BUI medians.

Non-Spread Day Events	*n*	FFMC		ISI		BUI	
		x̃ 0.95 CI	Max	x̃ 0.95 CI	max	x̃ 0.95 CI	max
All (1990 – 2019)	108	87 82.6 – 87.0	93	4.4 3.7 – 5.0	26.1	45 41.0 – 50.5	134
All lightning-caused wildfires (1990 – 2019)	77	86 82.0 – 87.0	93	4.4 3.2 – 5.0	18.2	43 35.0 – 46.0	134
All human-caused (1990 – 2019)	31	87 77.0 – 87.5	93	4.8 2.4 – 5.8	26.1	50 41.0 – 59.0	89
Period 1 (1990 – 2004) All	60	85 79.5 – 87.0	93	4.4 3.0 – 5.0	18.2	38.5 34.0 – 43.0	89
Period 2 (2005 – 2019) All	48	87 81.0 – 88.0	93	4.6 2.7 – 5.5	26.1	57 47.5 – 68.0	134
Period 1 (1990 – 2004) lightning-caused	47	83 78.0 – 87.0	93	4.4 3.1 – 5.1	18.2	35 30.9 – 38.0	74
Period 2 (2005 – 2019) lightning-caused	30	87 81.0 – 89.0	93	4.3 2.1 – 5.5	8.6	68.5 52.0 – 80.0	134
Period 1 (1990 – 2004) human-caused	13	87 77.0 – 87.5	90	4.4 1.7 – 5.1	8.2	66 39.0 – 69.0	89
Period 2 (2005 – 2019) human-caused	18	87.5 78.0 – 89.0	93	5.0 1.8 – 6.5	26.1	47.5 37.0 – 56.0	82

4.6 Discussion

May wildfire starts resulted in structural losses from wildfires in 2001 (60 structures including 10 homes), 2011 (456 homes and 23 non-residential building), 2016 (2,400 homes and commercial structures) and 2019 (16 homes). The 2016 Horse River Wildfire alone resulted in $3.84 billion in insured losses. Spring is a potentially dangerous wildfire season, in part because the live foliar moisture content is at a minimum just before the emergence of coniferous tree needles when nonstructural carbohydrates stored in the roots are translocated to support needle growth (Jolly et al. 2014). This seasonal change in foliar density and hence relative foliar moisture content occurs before the surge in photosynthetic spring recovery.

Referred to as the "spring dip", this short phenomenon (early May to mid-June) occurs after snow melt, and before green-up. Hirsch (1996) showed dates of the minimum foliar moisture content (~85%) across Canada as calculated by the Canadian Forest Fire Danger Rating System (CFFDRS). When Wildfire MWF009-2016 ran into Fort McMurray on May 4th, the forest was just starting to green-up. Wildfire management staff also observed the same phenology when Wildfire SWF065–2011 entered the Town of Slave Lake on May 15th.

Air masses originating in northern Canada are dry in the spring because water bodies are frozen and there is little to no plant photosynthesis, and hence minimal transpiration feeding moisture into the atmosphere. When fine fuels such as surface litter, leaves, mosses, needles, and twigs (< 1 cm diameter) reach moisture content levels of ≤12 % (FFMC ≥89), the ISI becomes very responsive to small changes in the wind speed (Lawson and Armitage 2008).

During our exploratory analysis of the weather data we noted the occurrence of days when our estimated ISI value using ERA5 weather outputs was less than 9 but significant wildfire growth was reported. Gusts occurred on these days. Incorporating gusts to support wildfire preparedness and suppression planning is particularly challenging. Wildfire modeling typically inputs the 10–minute average wind speed of the last 10 minutes before the hour. If the gust wind speed is used the modeled wildfire growth will likely be over-predicted. Likewise, if the 10-minute average wind speed is used and turbulence and gusts occur, the modeled output will likely under–predicted (Scott 2012).

Since ISI responds non-linearly to wind speed, short periods (e.g. 1-minute average of samples taken every 0.25 seconds) of high wind speed have more impact on wildfire behavior than longer averaged periods (e.g. standard 10-minute average of 0.25 second samples). Short periods of gusts can potentially generate firebrands and initiate crowning (Scott 2012).

We consider the approach described by Crosby and Chandler (2004) and its use by wildfire behavior analysts to predict wildfire behavior (Scott 2012), as reasonable in the absence of empirical data on the behavior of gusts, and in particular, the frequency and timing of these gusts. In Alberta, the reported gust is the peak gust during the hour. Periods of gusts associated with a frontal passage are typically of short duration whereas periods of gusts associated with a pressure gradient force can be sustained throughout the day and night.

We observed an underestimation of mean wind speeds of 0.8 m s^{-1} (1 km/h) in the ERA5 reanalysis. This may have caused a negative bias in ISI values and explains why the ISI ≥ 9 threshold was not reached for some days. Jourdier (2020) and Tetzner et al. (2019) also reported an underestimation of ERA5 modeled wind speeds.

Overall, a relatively small percent of days in the spring are wildfire spread event days in Alberta. Of the 92 calendar days when spread events from one or more wildfires occurred, about one-quarter experienced strong southeast winds associated with continental polar air masses. Cold fronts however, are the predominant feature with about half of the calendar spread days having pre–frontal or frontal passage activity.

While the synoptic weather patterns associated with strong south-southeast winds were less frequent than the cold front synoptic weather pattern, they resulted in unique challenges, including night–time burning and the inability to conduct aerial suppression operations due to the very high to extreme high winds. During the May 18 – 25 period in 1968, strong, dry southeasterly winds persisted all day and night which desiccated vegetation and contributed to the extreme wildfire behavior (McLean and Coulcher 1968). Fire behavior analysts need to understand and account for the cumulative impact of sustained strong, dry winds because live fuel moisture other than conifer foliar moisture is not directly accounted for in the FWI. As well, the daily FWI outputs use a standard day length and diurnal curves for temperature, relative and wind speed. These curves assume there is a night time recovery period.

Strong, desiccating winds can dry fuels before a wildfire starts (i.e. on non-spread days). In 2011, three days of dry southeast winds occurred May 7 – 9, and again, but stronger on May 11 – 13, before the wildfire outbreak on May 14 when Wildfire SWF65-2011 ran into the Town of Slave Lake. In 2015, strong, dry southeast winds occurred May 11 – 19, 2015 before the wildfire outbreak started on May 22.

Werth et al. (2011) identified four common weather elements contributing to extreme wildfire behavior: low relative humidity, strong surface winds, atmospheric instability, and drought. In The CFFDRS, the Drought Code (DC) provides an indication of the moisture content of deep organic layers, and the difficulty of extinguishing a wildfire. DC is an input to BUI. Our analysis suggests drought is not a prerequisite for extreme wildfire behavior during the spring season in Alberta. Very high (61 – 89) or extreme BUI (≥ 90) occurred on 30% (64) of the 212 spread day events. Our results indicate that spring wildfires in Alberta are primarily ISI driven. In their study of FWI system components for large wildfires across the boreal forest in Canada during from 1959 to 1999, Amiro et al. (2004) found that FFMC values were the highest during the spring and early summer, and particularly during the initial growth phase (a few days after ignition).

Although outside the scope of our study, a more thorough investigation of our data set is required to assess whether atmospheric stability and occurrence of low–level jets were contributing factors to extreme wildfire behaviour. The position of the polar jet stream relative to the location of wildfires is also an area of further study since the jet stream influences synoptic weather patterns. Air masses are typically colder north of the jet stream and warmer south of the jet stream.

4.7 Conclusion

The small percentage of wildfire spread days in the spring in Alberta are associated with critical synoptic weather patterns. The predominant surface weather feature contributing to extreme wildfire behavior on these days is the cold front passage (48% of calendar wildfire spread days). Cold fronts bring not only strong winds and changes in the wind direction, but also the potential for new wildfire starts from lightning. Strong south–southeast winds resulting from a surface high or ridge positioned west of Hudson Bay occurred on 26% of the wildfire spread days. Despite the lower frequency of occurrence, this weather pattern is critical because the strong, dry winds are often sustained for both multiple days and nights.

Human–caused wildfires in the spring cause the greatest structural losses. Wildfire management agencies have a suite of prevention tools to help reduce the risk of these wildfires. Fire bans and restrictions, forest area closures, and off-highway vehicle restrictions can be effective, but they need to be strategically issued and removed regionally and quickly (precision prevention). In

Canada, a program called FireSmart promotes a shared responsibility to build wildfire resilient communities. The seven disciplines of this program (education, vegetation management, emergency planning, legislation, development, interagency cooperation, and cross–training) contribute to both mitigation and prevention of wildfire. Unfortunately, FireSmart practices across Canada are underutilized to help mitigate structure losses from spring wildfires.

Canada's Changing Climate Report (Government of Canada 2019) states warming in Canada will on average continue more than twice the average global warming rate. Managing spring wildfires to protect multiple and competing values-at-risk is becoming more challenging because of climate change impacts including extended wildfire seasons (Albert-Green et al. 2013; Jolly et al. 2015; Jain et al. 2017), increased extreme fire weather (de Groot et al. 2013; Wang et al. 2015; Flannigan et al. 2016), increased area burned (Flannigan et al. 2005; Hanes et al. 2019), increased wildfire occurrence (Wotton et al. 2010), and reduced suppression capability (Podur and Wotton 2010; Wotton et al. 2017).

Spring wildfires with very high BUI values require more suppression effort to contain them because larger diameter dead and downed fuels, and deeper organic fuels are available for combustion. High average BUI values were observed in 2019, and very high BUI values in 2015 and 2018 during May. BUI however is not a prerequisite for extreme wildfire behavior. The common drivers for extreme wildfire behavior in the spring are very high to extreme FFMC and ISI. Because spring wildfires in Alberta are wind driven, extreme wildfire behavior can occur quickly and become very challenging to manage.

We observed a significant increase in ISI from Period 1 to Period 2 for lightning wildfires due in part to higher FFMC values in Period 2. BUI also increased from Period 1 to Period 2 for lightning wildfires suggesting a drier boreal forest in the future will result in more lightning starts. The increasing trend in large lightning-caused wildfires in Alberta's boreal forest during the 2015 – 2019 period may be linked to climate change. Our results provide a foundation for future work to help understand climate change impacts on wildfire activity. This includes changes in spring oceanic-atmospheric patterns (El Niño Southern Oscillation and Pacific

Decadal Oscillation) that impact temperature, lightning occurrence and lightning wildfire arrivals.

Research is also required to better understand wind extremes and the variability in wind speeds associated with gusts. New approaches to adjust wind speeds when gusts are forecasted are needed to support wildfire operations. Prediction of wind events was identified as a key research area by the Flat Top Complex Wildfire Review Committee (Flat Top Complex Wildfire Review Committee 2012).

Understanding the relationship between weather patterns at the surface and aloft, and the observed wildfire behavior is critical for preparedness and the ability to make 5 day and longer forecasts of the wildfire environment. Wildfire behavior analysts need a better understanding of the synoptic weather patterns responsible for extreme wildfire behavior. This however, requires strong linkages and integration between fire weather forecasters and fire behavior analysts.

Our results suggest wildfires will continue to escape suppression efforts to contain them as they become larger and more intense due to climate variability and change. Albertans therefore need to prepare and learn to live and work in a landscape with more wildfire.

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5. Conclusion

May wildfire starts in Alberta accounted for 23% of all wildfires, but were responsible for 55% of the total area burned during the period 1990 to 2019. On average, May has more wildfire starts than any other month. As well, significant structural losses from wildfires in 2001, 2011, 2016 and 2019 occurred during the month of May. Lightning on average (1990 – 2019) accounts for 44% of all wildfire starts during the wildfire season. Human activity and unknown causes are responsible for 56% of all wildfire starts. However, during May alone the cause percentages change with lightning, and human/unknown causes accounting for 17% and 83% of all wildfires respectively.

Human-caused wildfires are preventable. Prevention regulatory tools can be effective to reduce the number of May wildfire starts particularly during the period between snowmelt and greenup when current and forecasted wildfire danger conditions are very high to extreme. During very strong El Niño years such as 1997-98 and 2015-16, forest area closures and fire bans should be automatic. No forest area closures or fire bans were in place in northeast Alberta when the Horse River Wildfire raced through the Fort McMurray Urban Service Area on May 4, 2016. Public and industry support for fire restrictions, fire bans, forest area closures, and off highway vehicle restrictions is important. Disruption to tourism and industry activities can be minimized if these regulatory tools are temporally and spatially applied strategically. They therefore need to be activated and removed quickly and applied to only those areas that have the greatest risk. Trihadmojo et al. (2020) suggest prevention policy intervention needs to be targeted and mindful of traditional uses of fire. Changing behaviors also requires effective education. More research is needed to understand the effectiveness of regulatory tools and their optimal application.

It is not desirable for an ecological standpoint to eliminate all wildfire because of the multiple ecosystem services they provide. Nor is it economically viable to eliminate all wildfires. Despite Alberta having an overall effective wildfire management program (MNP 2020) wildfires continue to escape initial attack and being held phases of control. It is not possible to suppress all wildfires, all of the time. The public and politicians need to understand that wildfire management agencies have limits to their suppression capacity and capability. More importantly however, is the need for emergency management plans. In Alberta, local level government operates within 357 municipalities. This includes 269 urban municipalities (cities, towns, villages and summer villages), 5 specialized municipalities, 75 rural municipalities (64 municipal districts, 8 improvement districts and 3 special areas), and 8 Metis settlements. All municipalities need up to date and effective evacuation plans.

Chapter 2 documented the current state of wildfire management in Canada with a focus on preparedness. Most agencies use escalation protocols to activate activities corresponding to a particular preparedness level, but there is no consistent approach to determine the preparedness levels. Although all agencies use the Canadian Forest Fire Danger Rating System there are considerable differences in the level (amount and type) of decision support tools used for preparedness and response.

The six phases of wildfire management: prevention, mitigation, preparedness, response, recovery and review, are described in Chapter 2. Preparedness is about being in a state of readiness to adequately manage wildfires when they do arrive. Wildfire management agencies import resources to support on-going wildfires (i.e. sustained action), but less so to support preparedness. In their final report, the committee reviewing the 2011 Flat Top Wildfire Complex recommended that the Wildfire Management Branch “initiate resource requests in advance of potential demand especially in anticipation of extreme wildfire risk conditions” (Flat Top Complex Wildfire Review Committee (2012) . Research is required to understand why this not happening and also to estimate the optimum level and configuration of resources across Canada required to meet future resource demands by the wildfire management agencies.

To confront a future with more challenging wildfires a wildfire management paradigm shift is proposed. This is conceptualized as a triangle in Chapter 2. Agencies need to individually and collectively strengthen and re-align their wildfire management capacity and capability to support a risk-based appropriate response approach. Values protection (FireSmart) also needs to be enhanced. These two requirements allow for more managed wildland fire to be used on the landscape. Since FireSmart is a shared responsibility, social science research is required to help identify the barriers and opportunities to successfully implement FireSmart across Canada.

Based on average land and sea surface temperatures, 2020 was the second warmest year on earth (0.98ºC above average). The third warmest year was 2019 (.95ºC above average), and the warmest year was 2016 (1.0ºC above average). The average is based on a twenty year period (1981 – 2010) (National Centers for Environmental Information 2021). The Canada Climate Change Report 2019 warns that climate change will result in more frequent and intense weather extremes (i.e. more severe drying periods) (Government of Canada 2019). Increased warming, and a precipitation shift toward less snowfall and more rainfall, and the resultant smaller snow packs and earlier snowmelt (Knowles 2006; Berghuijs et al. 2014) will impact spring wildfire seasons. This is a concern for Alberta which continues to experience disastrous spring wildfire seasons.

Because May is the most critical month for wildfire activity in Alberta, spring specific enhanced situational awareness is required for the Wildfire Management Branch in Alberta to be prepared for potential extreme wildfire events. Chapter 3 introduced one approach based on the use of statistical surveillance thresholds for enhanced situational awareness in the spring in Alberta. Initial attack (IA) and being held (BH) escape surveillance charts with statistical surveillance thresholds estimated using the peak over threshold approach were developed as prototype tools for enhanced situational awareness. The surveillance of spring IA and BH escapes combined with sea surface temperature surveillance can provide decision support as part of an early warning system of spring wildfire risk and potential application of a code red declaration (highest state of readiness).

Chapter 4 described the initial fire weather conditions for 80 large wildfires in Alberta that started in May and grew to over 1,000 ha during the 1990 – 2019 period. The hypothesis that the synoptic weather pattern associated with the 1968 wildfire outbreak is the predominant pattern continuing to occur in the spring during wildfire spread days is rejected. Strong south-southeast winds from a surface high centered west of Hudson Bay and a surface low located southwest of the high occurred on 26% of the calendar spread days. In comparison, pre-frontal and frontal passage activity occurred on 48% of the calendar spread days. The fire danger analysis indicates the spring season in Alberta is an ISI driven fire regime with very high to extreme FFMC and ISI values. Although spring wildfires are wind driven, very high BUI values have occurred and challenged wildfire suppression efforts, but they are not a prerequisite for large wildfires in May.

Zeng et al. (2019) analyzed wind speed data globally from 1978 to 2017. They found that since 2010 wind speed has been increasing possibly due to decadal ocean-atmosphere oscillations. There is however considerable uncertainty regarding climate change impacts on wind speed when downscaling. This is an area of further research.

There are several opportunities for enhanced situational awareness and preparedness for the occurrence of the two main synoptic weather patterns. When strong and sustained dry winds occur throughout the night, the FWI System may be underestimating the impact on fuel moisture as the FWI System has a built in diurnal curve that decreases temperature and wind speed and increases relative humidity at night (referred to as night time recovery). Double staff shifts to monitor fire weather and behavior during the night should be considered when strong and sustained dry winds are forecasted. Regulatory prevention tools are effective in the spring because most of the wildfires starts are human-caused. Lightning activity is low in the spring; most strikes in Alberta occur during July and August.

The surface Arctic high that was present on May 14, 2011 when wildfire SWF-065 entered the Town of Slave Lake, started developing on May 6th. Forecasting in advance when an upper blocking pattern aloft develops and a surface high pressure area from the Arctic (Hudson Bay High) moves south is important to provide sufficient time for resources to be moved from within the province, and if required, additional resources to be imported from outside Alberta or Canada.

Cold front passages are the predominant feature associated with spread days in the spring in Alberta. They result in changes in temperature, relative humidity, and wind speed and direction. Forecasting the speed and hence timing of fronts, and the potential for lightning provides critical intelligence for the wildfire behavior analyst who predicts when and where existing or potential wildfires will spread. Understanding winds in the middle and upper levels of the atmosphere is also important as they can influence the winds at the surface. This includes thermal turbulence (instability indicated by temperature gradient and inversion breakdown timing, wildfire induced buoyancy), frontal turbulence (strength and timing of frontal passage), mechanical turbulence (surface friction and topographic effects), and wind turbulence (wind shear and low level jet). Wildfire behaviour forecasts therefore need to bridge the weather conditions and trends aloft with the weather conditions at the surface. This requires a strong working integration of wildfire weather and wildfire behavior staff.

The common theme of Chapters 2 to 4 is wildfire preparedness to support response. Preparedness is about readiness for today's wildfire situation and readiness in anticipation of a future situation. As noted in Chapter 1, climate change impacts will continue to challenge the capacity and capability of wildfire management agencies to effectively and efficiently manage more intense wildfires while ensuring the protection of values-at-risk on the landscape. Enhanced situational awareness of the wildfire environment using statistical visualization techniques and new innovative tools, and strengthened preparedness will contribute to supporting a wildfire management paradigm shift as proposed in Chapter 2 that allows Albertans to safely coexist with wildfire. While progress has been made in response to the Canadian Wildland Fire Strategy, considerably more needs to be done to advance wildfire management in Canada and in particular being more ready, and right ready for a future with more wildfire.

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Appendix A: Chapter 2 Supplementary Information

The approach to managing wildfires in Canada is based on either zonation or no zonation, and full or appropriate response. The protection of human life and communities is the first priority of all wildfire management agencies. The suppression priority of other values-at-risk across Canada vary by agency. We include wildfire management zone maps for each provincial and territorial agency to illustrate the varying approaches used across Canada. The dark green areas on these maps delineate Canada's national parks. The Parks Canada Agency is responsible for managing wildfires within these lands. We also selected examples of decision support tools to support response and preparedness to show the range of products used by wildfire management agencies.

Yukon Territory (YT)

YT has five wildfire management zones (Fig. A1). The Critical Fire Management Zone includes homes and the highest value infrastructures. Wildfires within this zone receive the highest suppression priority. The Full Fire Management Zone is second in suppression priority. Wildfires in the Strategic Fire Management Zone are strategically managed with a focus on both protecting values and minimizing suppression costs. Wildfires burn with minimal interference in the Wilderness Zone which accounts for about 80% of the YT, but has the lowest infrastructure values. In the Transitional Fire Management Zone wildfires are managed using an appropriate response approach. This zone is primarily a buffer between the Wilderness and Strategic Fire Management Zones. Depending on the time of year and weather trends zone types can change (e.g. after mid-July consideration is given to change Strategic and Transitional Zones to Wilderness Zones).

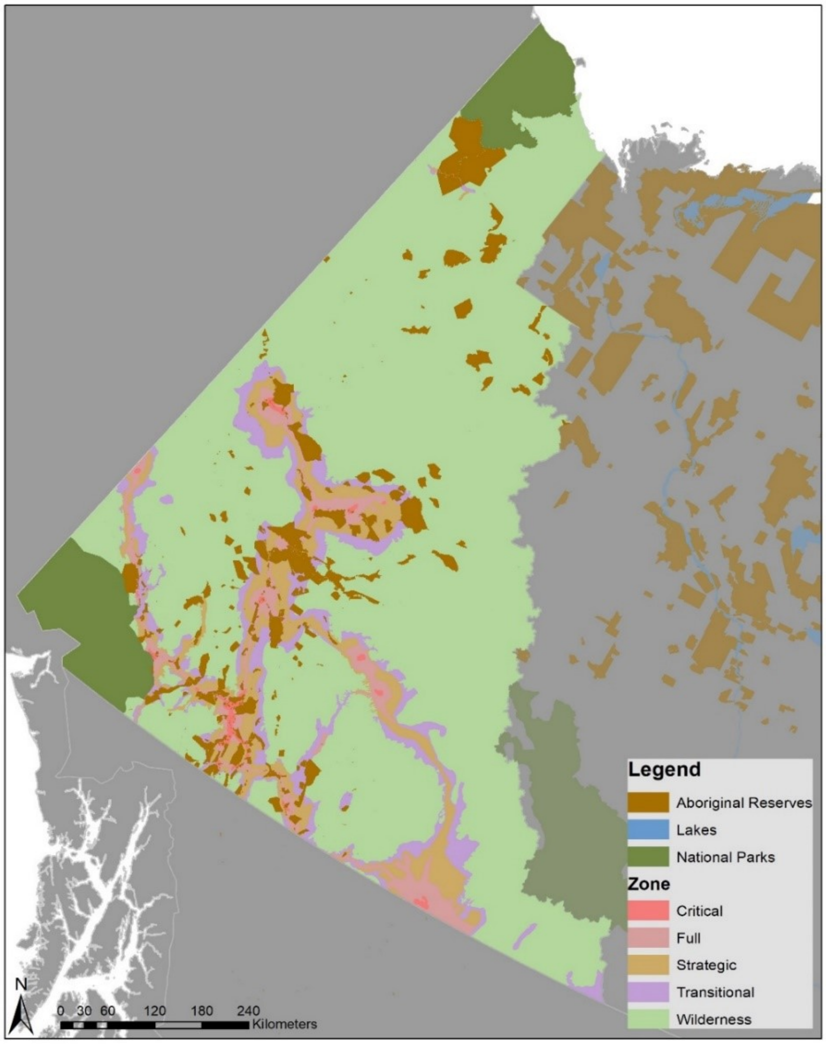

Figure A1. Yukon Territory Wildfire Management Zones (Government of Yukon Territory 2003, 2015)

Northwest Territories (NT)

The Northwest Territories (NT) Government provides wildfire management services on approximately 614,000 ha classified as forested land. Because of the low population and few values-at-risk across the territory, the wildfire management program has one of the smallest suppression programs in Canada with an annual budget of $7.5 million. NT is managed as one appropriate response wildfire management zone (Fig. A2) where the response type is based on a wildfire-by-wildfire basis. Fire management in the Northwest Territories includes community consultation to address the needs of local residents and incorporate upon local knowledge (Government of Northwest Territories 2005).

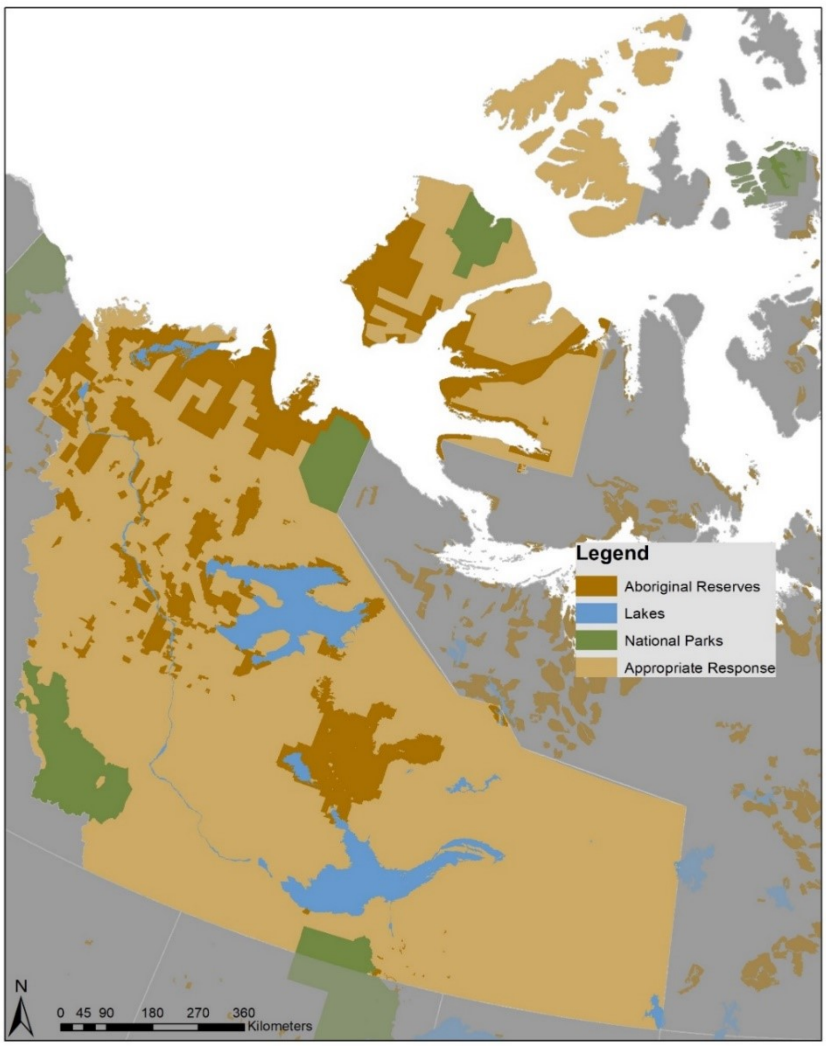

Figure A2. Northwest Territories Fire Management Zone.

British Columbia (BC) and Alberta (AB)

Although the entire province of BC is full response (Fig. A3) the wildfire management approach is based on protecting lives and values-at-risk, and also supporting sustainable and healthy ecosystems by managing beneficial wildfire (Government of British Columbia 2010). A wildfire analysis process is used to assess all wildfires and ensure appropriate response types that are aligned with the land management objectives. The independent review of the disastrous flood and wildfires in 2017 (Abbott and Chapman 2018), and the internal Provincial After-Action Review (Government of British Columbia 2018) did not recommend a change to this approach.

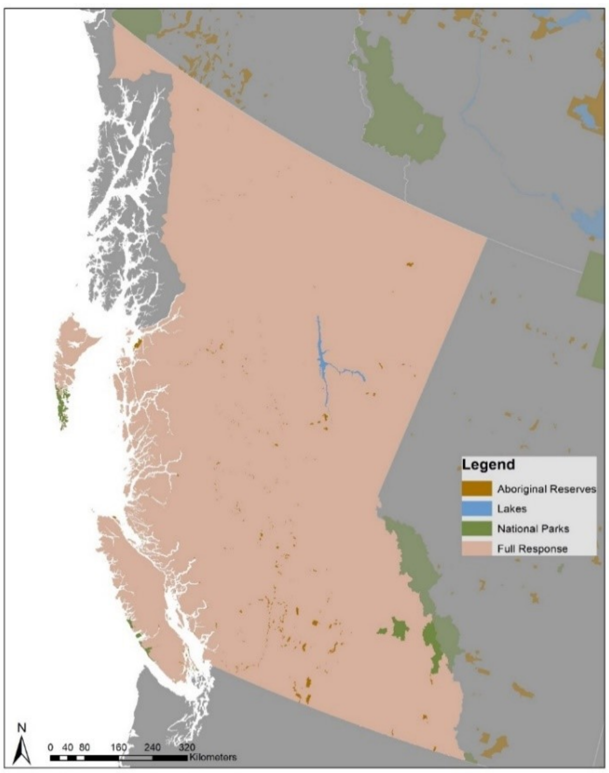

Figure A3. British Columbia Wildfire Management Zone.

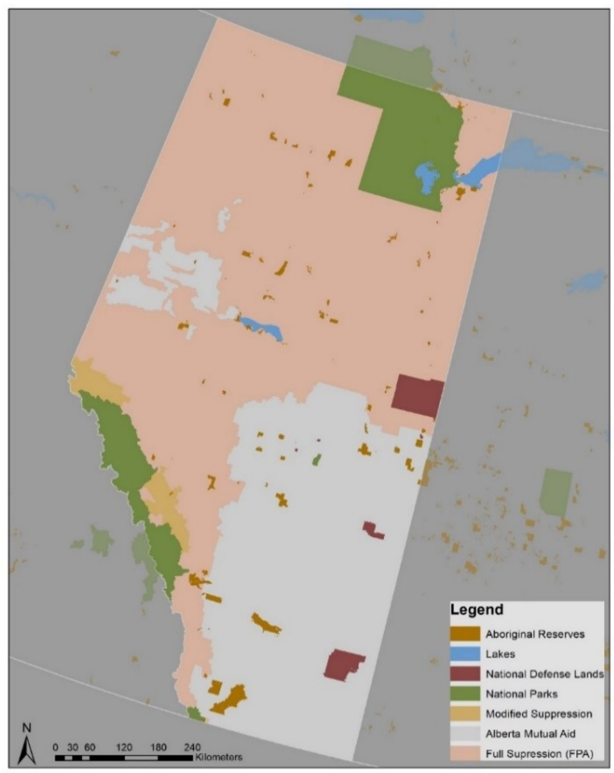

Figure A4. Alberta Wildfire Management Zone.

Table A1. British Columbia Wildfire Service Preparedness Level Table (Government of British Columbia 2016). Intensity Group 1 = smouldering ground wildfire (< 10 kW/m), Intensity Group 2 = low vigour surface wildfire (10 – 500 kW/m), Intensity Group 3 = moderately vigorous surface wildfire (500 - 2000 kW/m), Intensity Group 4 = passive crown or very vigorous surface wildfire with torching (4,000 kW/m), Intensity Group 5 = active crown or extremely vigorous surface wildfire (4,000 – 10,000 kW/m), Intensity Group 6 = Blowup wildfire with extreme wildfire behavior (> 10,000 kW/m)

Forecasted Daily Fire Starts	Preparedness Level				
15+	4	5	6	6	6
11 – 14	3	4	5	6	6
6 -10	2	3	4	5	6
3 – 5	1	2	3	4	5
0 -2	1	1	2	3	4
Intensity Group	1	2	3	4	5

Table A2. British Columbia Preparedness Condition Table (Government of British Columbia 2016). RSWAP is a Resource Strategic Wildfire Allocation Protocol used to inform the prioritization of wildfires and allocation of resources.

Preparedness Condition	Wildfire Activity	Resource Exchange Status	RSWAP	Long Term Strategic Planning
1	Normal	Exporting	No	No
2	Increasing	Exporting/Holding	No	No
3	Increasing	Holding	Implemented	Yes
4	High	Holding/Importing	Fully established	Yes
5	Very significant	Importing	Fully established	Yes

Forest history has shaped wildfire management policy in Alberta (AB). Settlers clearing land in 1968 caused a disastrous spring wildfire season when many of the debris-burning fires escapes into the adjacent lands (Kiil and Grigel 1969). The following year the Forest Protection Area (FPA) was officially defined thereby separating the forest area from the agricultural area (Murphy 1985). The FPA is a full response zone with the exception of two areas (Willmore Wilderness and R11 Forest Management Unit) that have wildfire management plans supporting modified suppression.

Table A3. Alberta preparedness levels, wildfire situation assessment and coordination issues (Government of Alberta 2018c).

Prep Level	Wildfire Situation Assessment	Coordination Issues
5	- Many areas with extreme fire danger - Anticipated fire load (7 days) is extreme - There is a single very large wildfire or a number of large fires out of control - Wildfires display extreme fire behavior with significant growth potentials for multiple days	- There is a potential for creating wildfire complexes - There is a significant community or industrial infrastructure that is impacted - Severe shortage of resources over multiple deployments - Wildfire management representative is present in a local EOC
4	- Very high overall fire danger with areas of extreme fire danger - Anticipated fire load (7 days) is heavy - Wildfires likely to escape containment - Significant fire behavior with short term large fire growth Potential	- Resource shortages over a 1 to 2 deployment timeframes - Importing of resources required - Multi-agency involvement (could include Unified Command) - Municipal EOCs activated
3	- High overall fire danger with potential for pockets of very high and extreme fire danger - Anticipated fire load (7 days) is high - Increased risk of wildfires escaping containment - Potential for values to be threatened - Potential for smoke or public health impacts	- Resources not adequate for all areas - Importing minimal single resources or small number of crews occurring or anticipated - Potential for multi-agency involvement - Media interest increasing - Potential resource shortages forecasted or resources not Adequate
2	- Moderate overall fire danger with potential for pockets of high fire danger - Weather forecasts show increased fire danger or short duration severe events (i.e. high winds) - Fire load increasing but manageable (low-moderate)	- Adequate resources in Province for all incidents - Minimal movement between Areas may be required for individual or crew resources - Resources available for export
1	- Low fire danger - Current and anticipated fire load is low	- Adequate resources in Areas - Resources available for export

Table A4. Alberta Prep (Preparedness) Level and corresponding Alberta Wildfire Coordination Centre (AWCC) considerations (Government of Alberta 2017).

Prep Level	AWCC Considerations
5	- Discuss fire bans, forest closures and activity restrictions - Multiple Consequence Management Officers covering extended operations in AEMA POC - Consider provincial wildfire spokesperson - Consider importing IMTs - Consider CIFFC representative in AWCC
4	- Consider activating Deputy Duty Officer (DO) and Deputy Aircraft Coordinator (PAC) - Daily conference calls between AWCC and Area Fire Centres - AWCC logistics function increased in capacity - Staff and facilities dedicated to briefing and receiving imported resources - Mandatory participation by all qualified headquarters wildfire management staff - Consider shifting key positions - IMT level 1 activated and/or prepositioned; multiple IMTs possible - Non-Wildfire Management Staff requested - Discuss fire bans - Consequence Management Officer may be activated into AEMA POC due to wildfire - Media activity is high; high demand for the FWI fire line.
3	- Provincial Fire Behaviour Specialist based in AWCC - Weather forecasts include fire behavior predictions - Provincial priorities set by AWCC and communicated - IMT level 2 teams are engaged in Forest Areas or placed on standby provincially - Effective information flow to AEMA POC is increased - AWCC logistics function activated - Staff expected to work extended hours - Resources requested through CIFFCX and/or Northwest Compact - AWCC may directly move Forest Area resources to higher priorities - Discuss fire restrictions - Intelligence function activated in AWCC
2	- Multi-fire potential but significant fire growth not expected - AEMA POC updated as required - Key AWCC positions put on standby - Importing resources not required - Consider fire advisories <u>Exporting Resources Out-of-Province</u> - AWCC Duty Officer consulted prior to exporting resources - Exporting multiple crews and overhead - Anticipating multiple deployments - Additional AWCC positions may be activated - Potential for media interest
1	- Low fire danger - Current and anticipated fire load is low <u>Exporting Resources Out-of-Province</u> - AWCC Duty Manager consulted prior to exporting resources - Exporting single resources and individual crews

Saskatchewan (SK)

Wildfire management in Saskatchewan is based on zonation (Fig. A5) (Government of Saskatchewan n.d.). Wildfires are allowed to burn (monitor response) in the Northern Zone unless northern communities are threatened. Full suppression occurs in the Primary Timber Area with the goal of containing all wildfires to less than 10 ha in size. Wildfires in the Secondary Timber Area are managed to reduce the impact on important forest resources and ensure forest allocations in the Primary Timber Area are not threatened. The Burn Notification Area is a buffer zone where permits (Burn Notification Number) are required for open fires within 4.5 km from a provincial forest.

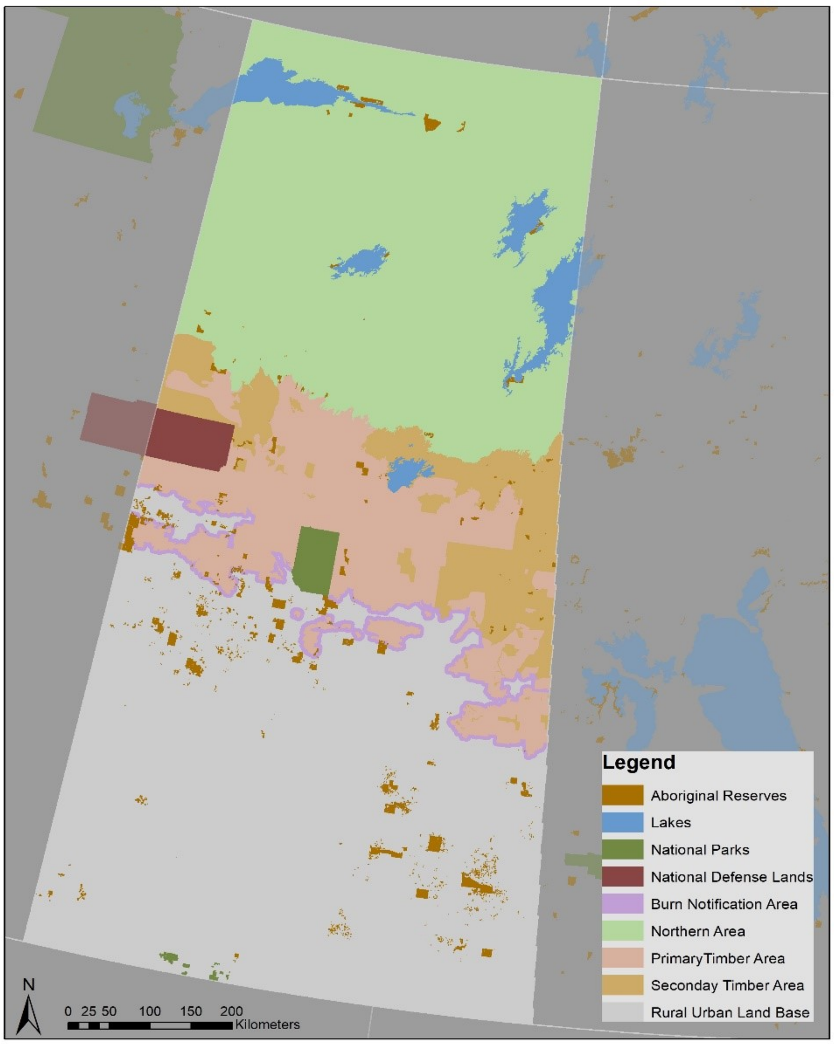

Figure A5. Saskatchewan Wildfire Management Zones

SK uses an Operational Decision Tree to guide appropriate responses within all zones (Fig. A6) (Government of Saskatchewan 2016).

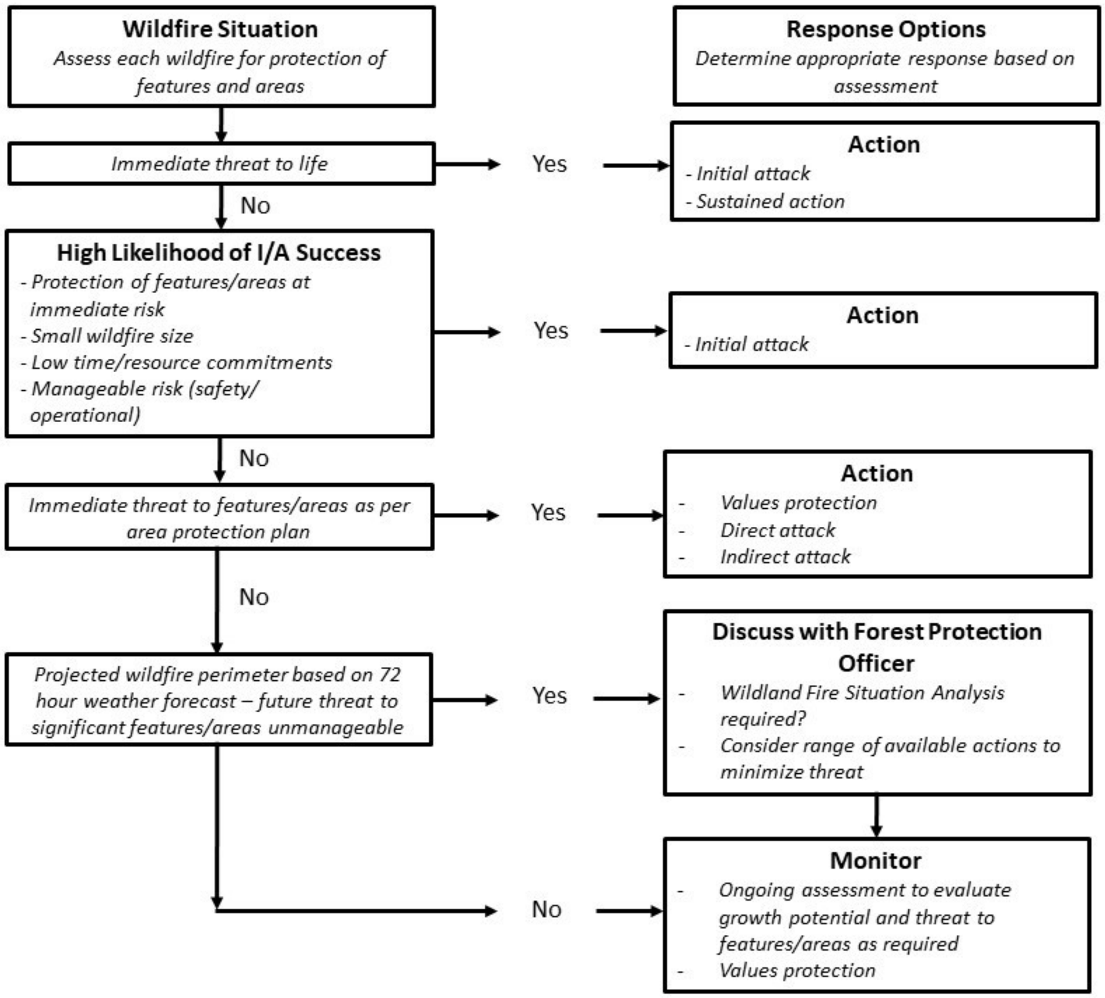

Figure A6. Wildfire management operational decision tree used in Saskatchewan. The frequency of monitoring activities is based on a balance of protecting features/areas, providing ecological benefits and managing suppression costs (Government of Saskatchewan 2016)

Preparedness and response were severely tested during the 2015 wildfire season when 720 wildfires burned about 5% of the forest in Saskatchewan. Of the total 1.7 million ha burned, 700,000 ha occurred in the full response areas.

Manitoba (MB)

Three priority zones within the Primary Protection Zone guide the level of effort required to manage wildfires. North of the Primary Protection Zone wildfires are allowed to burn unless northern communities and critical infrastructure are threatened. Preparedness levels in MB are determined using six decision charts (Fig. A8) (Government of Manitoba 2010).

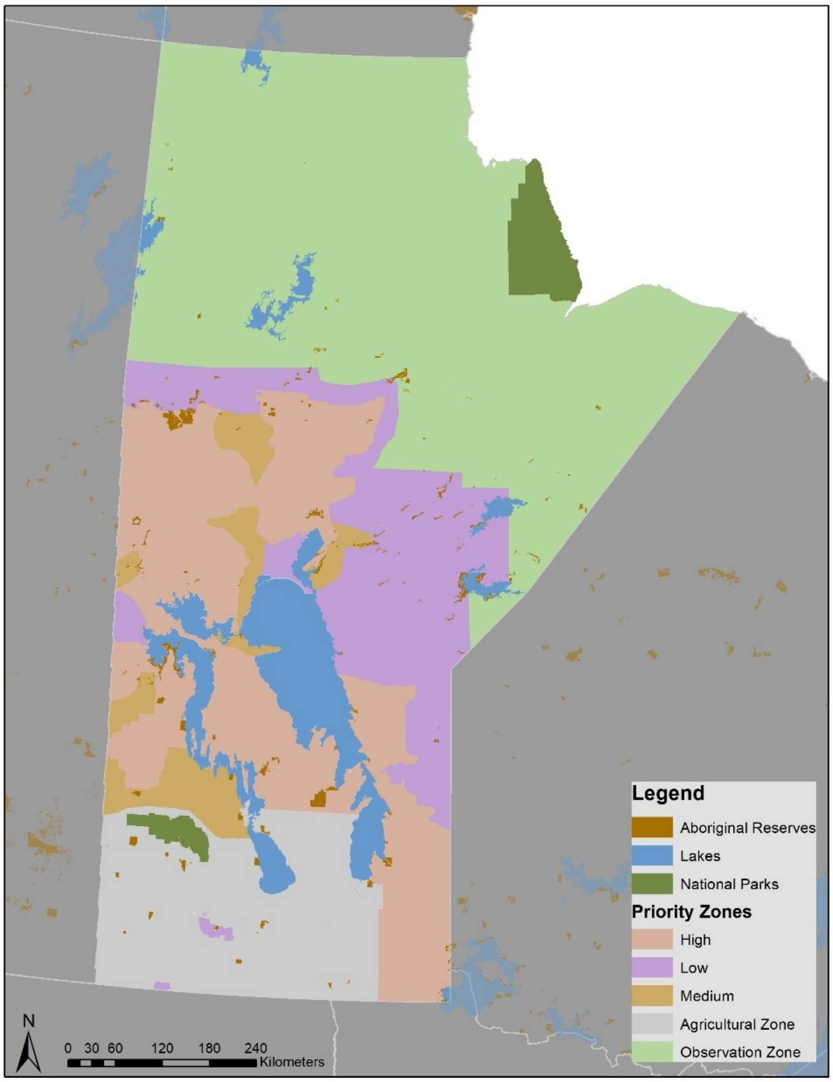

Figure A7. Manitoba Wildfire Management Priority Zones

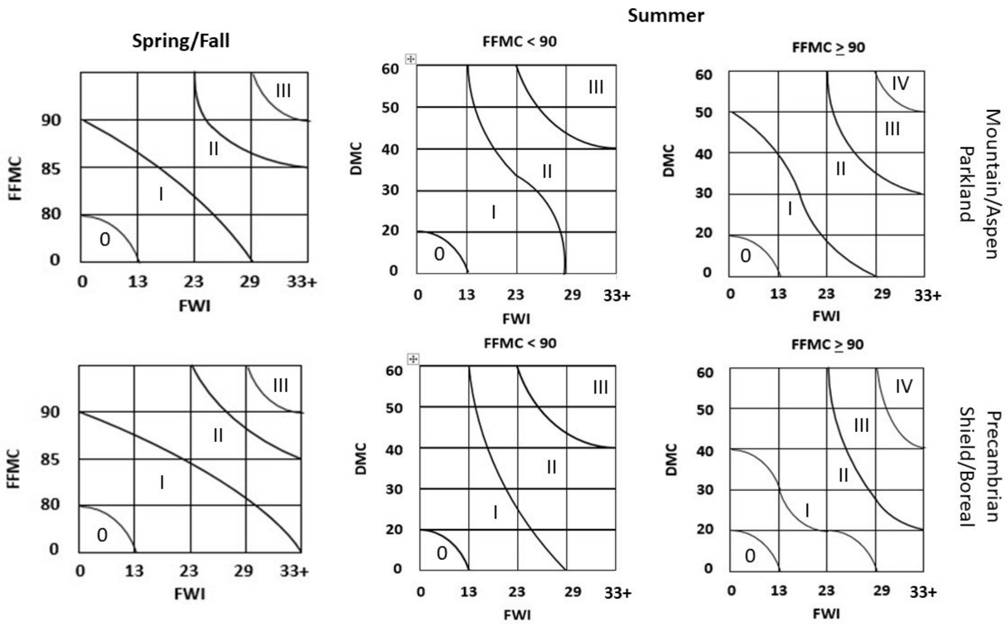

Figure A8. Manitoba preparedness levels (0 – IV) based on Fine Fuel Moisture Code (FFMC) and Fire Weather Index (FWI) in spring/fall, and Duff Moisture Code (DMC) and FWI in summer (Government of Manitoba 2010).

Ontario (ON) and Quebec (QC)

With the exception of the area designated as non-forested land in Fig. A9, ON is zoned as appropriate response (Government of Ontario 2014). ON is developing a modeling suite of decision support tools to provide a defendable and repeatable risk-based approach to appropriately respond to wildfires in this zone (Government of Ontario 2016). Quebec in comparison uses three zones: Full response, modified response and no response (Monitored) (Figure S9). The Société de protection des foréts contre le feu (SOPFEU) is a non-profit organization that provides wildfire detection and response services to the Quebec government, forest industry and large private woodlot operators. Their objective is to deliver effective and cost efficient wildfire suppression. SOPFEU uses a decision tree (Société de protection des foréts contre le feu 2015) to develop a daily deployment plan based on spatial wildfire intensity outputs and lightning occurrence prediction.

ON uses a Response Phase Criteria Chart (Table A5) to determine a response phase that is aligned with the agency preparedness levels submitted by the Provincial Duty Officer to CIFFC (Government of Ontario 2015).

Table A5. Ontario Phase Criteria Chart. FFFM (Fine Fuel Moisture Code), BUI (Buildup Index) and ISI (Initial Spread Index) are Fire Weather Index outputs. Intensity classes: 1: 10 kW/m, 2: 10 – 500 kW/m, 3: 500 – 2,000 kW/m, 4: 2,000 – 4,000 kW/m, and 5: > 4, 000 kW/m.

	Phase 1 Low	Phase 2 Moderate	Phase 3 High	Phase 4 Extreme	Phase 5 Escalated
FFMC (ease of ignition)	< 80	≤ 86	≤ 90	> 90	> 90
BUI (intensity)	< 20	< 36	≤ 60	> 60	> 60
ISI (spread rate m/min)	< 2.2	< 5.0	≤ 10.0	> 10.0	> 10.0
Intensity Class	1 - 2	2 - 3	3 – 4	4 - 5	4 - 5
Expected fire arrivals	Few, if any	≤ 3	3 +	Potential for multiple starts	Potential for multiple starts
Current resource commitment	< 10 %	< 20 %	< 50 %	< 50 %	> 50 %
Available resources	> 75 %	> 50 %	< 50 %	Resources may be recalled	Resources may be recalled

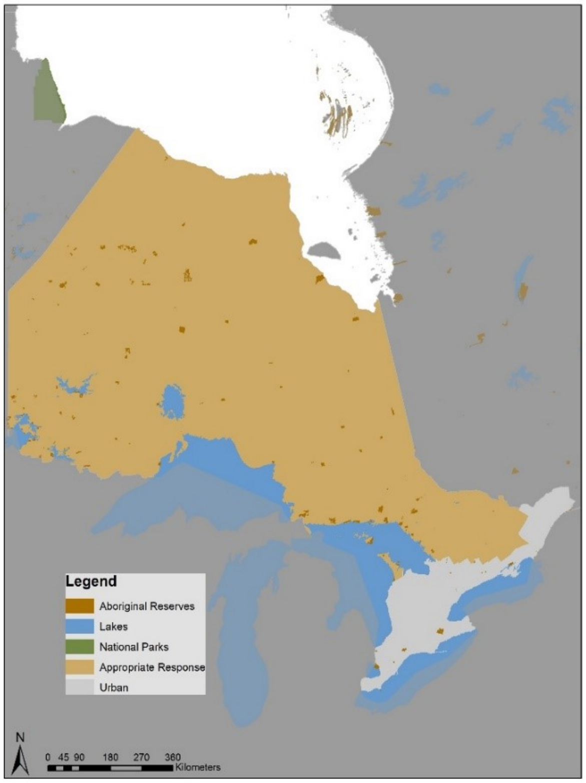

Figure A9. Ontario Wildfire Management Zone.

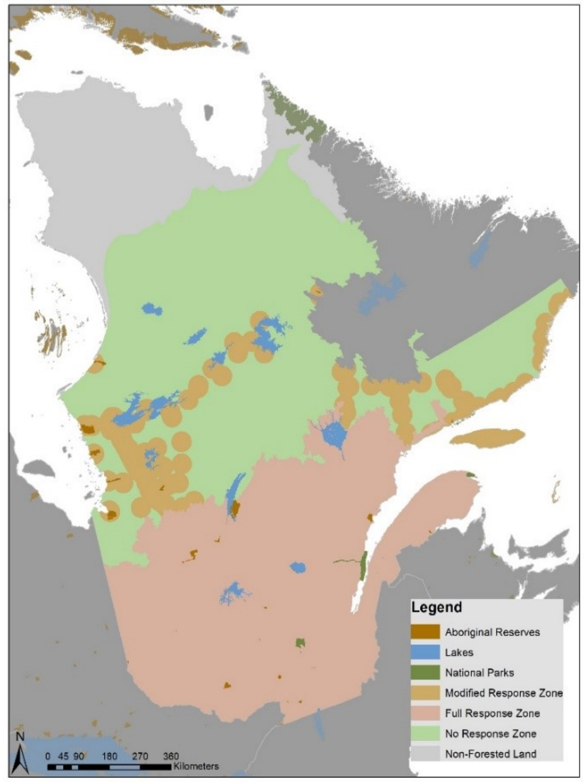

Figure A10. Quebec Wildfire Management Zones.

Atlantic Provinces

Full wildfire suppression occurs in the provinces of New Brunswick, Nova Scotia, and Prince Edward Island, and the island of Newfoundland. Labrador however has both full and monitored response zone.

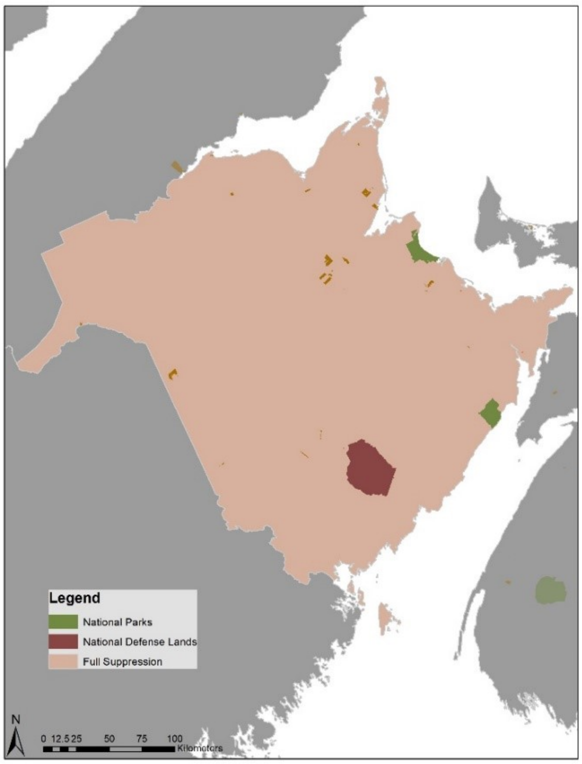

Figure A11. New Brunswick Wildfire Management Zone.

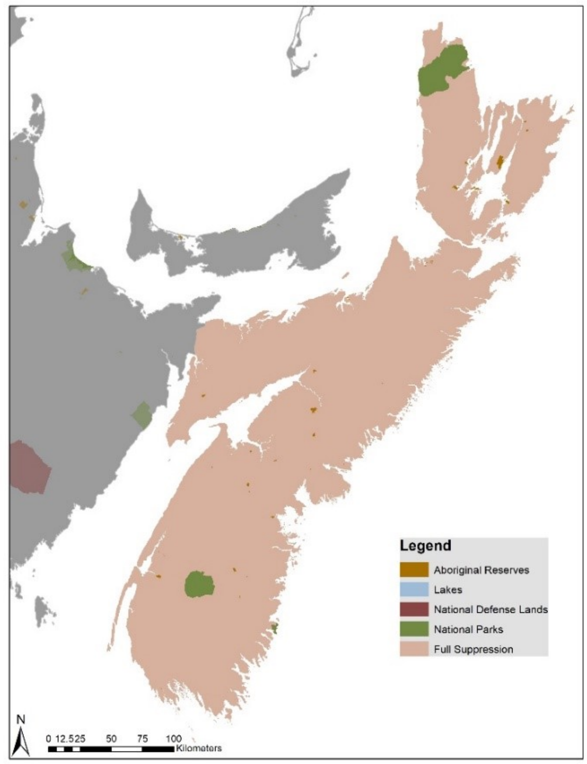

Figure A12. Nova Scotia Wildfire Management Zone.

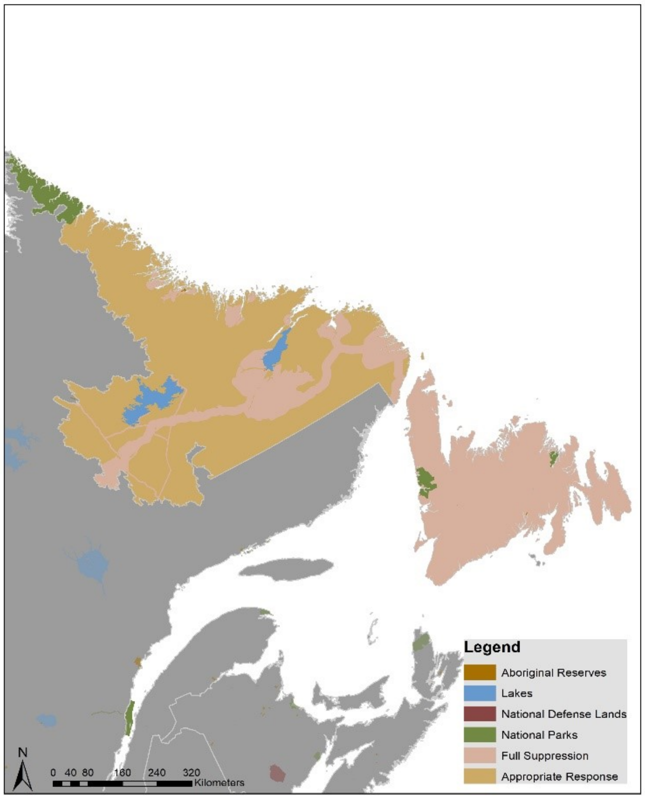

Figure A13. Wildfire management zones for Newfoundland and Labrador.

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Appendix B: Chapter 4 Supplementary Information

Table B1 FFMC, ISI and BUI mean and maximum values for each year and wildfire event spread days.

Year	Cause	Event No.–No. of wildfires (*n*)–No. of spread days	FFMC x̄ – max	ISI x̄ – max	BUI x̄ – max
1991	L	1-1-1	84	3.8	51
1993	L	2-1-4	**90.8** – 92	**13.9** – 16.4	28 – 31
1995	L	3-5-15	**91.6** – 93	**12.1** – 18.8	49 – 66
	H	4-1-4	**91.5** – 92	**13.4** –17.6	52 – 57
	L	5-1-1	87	**11.7**	55
	L	6-1-4	**92.8** – 94	**23.7** – 29.7	**78** – 83
1998	L	7-2-5	85.8 – 88	4.3 – 6.7	60 – 65
	L	8-3-6	85.9 – 89	7.9 – 13.5	52 – 73
	L	9-1-3	**90**	7.9 – 9.2	**66** – 69
	L	10-3-4	84 – 90	4.7 – 6.8	32 – 36
	L	11-3-10	**90.2** – 93	**18.1** – 24.6	27 – 32
	H	12-1-2	86.5 – 90	5.6 – 7.9	**76** – 79
	H	13-1-3	**92.3** – 93	**38** – 68.4	35 – 38
	L	14-1-2	85 – 86	4.1 – 5.9	46 – 47
	H	15-1-3	**89** – 92	**18.4** – 25.7	29 –32
1999	L	16-6-17	**89.2** – 93	**19** – 27.3	36 – 53
	L	17-1-3	**90** – 91	**19.4** – 30.3	35 – 39
2001	L	18-1-2	**89.5** – 90	**15.6** – 22.6	26 – 26
	L	19-2-4	84.3 – 87	**11.8** – 21.8	40 – 44
	H	20-1-2	**89** – 90	**32.3** – 45.1	**91** – 90
	H	21-1-3	**90.3** – 91	**14.1** – 16.6	58 – 60
	H	22-1-1	**89**	**13.7**	**72**
2002	H	23-1-3	88.5 – 92.5	**24.3** – 34.6	31 – 33
2003	H	24-1-2	**92.5**	**23.9**	49
2005	H	25-1-2	**91.5** – 92	8.7 – 9.8	54 – 55
	H	26-1-2	**89.8** – 91	7.5 – 9.6	40 – 40
2006	H	27-1-1	85.3	**12.5**	38
2008	H	28-1-3	**91.5** – 93	**17.8** – 32.8	46 – 51
2011	H	29-1-3	**94.2** – 95.5	**28** – 44.3	**76** – 80
	H	30-2-6	**91.4** – 93	**28.3** – 52	29 – 46
	H	31-4-16	**89** – 92	**26.8** – 53.7	14 – 20
	H	32-1-4	**94.9** – 96.4	**32.1** – 50.1	**73** – 79
	H	33-1-3	88 – 90	**26.9** – 46	13 – 17
2012	H	34-1-3	**93.7** – 95	**18.7** – 22	44 – 48
	L	35-1-2	**90.5** – 92	**15** – 17.7	39 – 40
	H	36-1-4	**93.7** – 94	**22.4** – 31.5	**95** – 102
2013	H	37-1-1	**93**	**30.8**	52

2015	L	38-3-7	88.9 – 94	8.8 – 13.8	**104** – 132
	L	39-1-4	**93** – 94	**9.1** – 11.9	**97** – 103
	H	40-1-4	**93.5** – 95	**10** – 11.9	55 – 60
	H	41-1-2	**92** – 94	**9.1** – 11.1	**76** – 79
2016	L	42-1-4	**93.5** – 95	**15** – 19.4	59 – 65
	H	43-1-4	**94** – 94	**11.7** – 13.1	49 – 57
2018	L	44-1-1	**90**	**19.6**	**73**
	L	45-1-3	**93.7** – 95	**11.1** – 12.5	**103** – 108
	L	46-1-1	66	2.9	41
	L	47-1-2	**92** – 93	**12.1** – 15	**90** – 91
	L	48-1-2	**89** – 90	**18.1** – 29	**80** – 81
	L	49-2-6	**93** – 94	**14.4** – 22.6	**92** – 99
	L	50-1-2	**91.5** – 94	**13.3** – 17.6	**70** – 71
	H	51-2-8	**91.9** – 93	**24.3** – 28.2	51 – 57
	L	52-2-3	**90.9** – 93	**18.1** – 23.2	40 – 50
	L	53-1-3	**92.2** – 93	**11.4** – 9.8	46 – 52
	L	54-1-2	**94.5** – 95	**14.1** – 14.6	**90** – 92