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Complete List of Authors:	Coogan, Sean; University of Alberta, Renewable Resources Daniels, Lori; University of British Columbia, Forest and Conservation Sciences Boychuk, Dennis; Ontario Ministry of Natural Resources and Forestry Aviation Services, Aviation, Forest Fire and Emergency Services Burton, Philip; UNBC Northwest, Flannigan, Mike; University of Alberta, Renewable Resources Gauthier, Sylvie; NRC, Canadian Forest Service, Kafka, Victor; Parks Canada Park, Jane; Parks Canada Agency Wotton, B. Mike; Great Lakes Forestry Centre, Faculty of Forestry
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Fifty years of wildland fire science in Canada

Sean C. P. Coogan, Lori D. Daniels, Den Boychuk, Philip J. Burton, Mike D. Flannigan, Sylvie Gauthier, Victor Kafka, Jane S. Park, B. Mike Wotton

Corresponding author: Sean C. P. Coogan (email: scoogan@ualberta.ca).

SCPC and MDF: Department of Renewable Resources, University of Alberta, Edmonton, AB T6G 2H1, Canada. Email: scoogan@ualberta.ca; mike.flannigan@ualberta.ca

LDD: Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, BC, Canada. Email: lori.daniels@ubc.ca

PJB: Ecosystem Science and Management Program, University of Northern British Columbia, 4837 Keith Avenue, Terrace, BC, V8G 3K7, Canada. Email: Phil.Burton@unbc.ca

SG: Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S, P.O. Box 10380, Stn. Sainte-Foy, Québec, QC, G1V 4C7 Canada. Email: sylvie.gauthier2@canada.ca

JSP and VK: Banff Field Unit, Parks Canada Agency, P.O. Box 900, Banff, AB, T1L1K2, Canada. Email: jane.park@canada.ca; victor.kafka@canada.ca

BMW: Natural Resources Canada, Canadian Forest Service, Forestry-University of Toronto, 33 Wilcocks Street, Toronto, ON, M5S 3B3, Canada. Email: mike.wotton@utoronto.ca

VK: Conservation Programs Branch, Parks Canada Agency, Government of Canada, 3, passage du Chien-d'Or, Suite 200, Québec, Québec G1R 3Z8, Canada. Email: victor.kafka@pc.gc.ca

DB: Aviation, Forest Fire and Emergency Services, Ontario Ministry of Natural Resources and Forestry, 400 – 70 Foster Dr, Sault Ste Marie, ON, P6A 6V5, Canada. Email: den.boychuk@ontario.ca

Abstract: We celebrate the 50th anniversary of the Canadian Journal of Forest Research by reflecting on the considerable progress accomplished in select areas of Canadian wildland fire science over the past half century. Specifically, we discuss key developments and contributions in the creation of the Canadian Forest Fire Danger Rating System; the relationships between wildland fire and weather, climate, and climate change; fire ecology; operational decision support; and wildland fire management. We also discuss the evolution of wildland fire management in Banff National Park as a case study. We conclude by discussing some possible directions in future Canadian wildland fire research including the further evaluation of fire severity measurements and effects; the efficacy of fuel management treatments; climate change effects and mitigation; further refinement of models pertaining to fire risk analysis, fire behaviour, and fire weather; and the integration of forest management and ecological restoration with wildland fire risk reduction. Throughout the paper we reference many contributions published in the Canadian Journal of Forest Research, which has been at the forefront of international wildland fire science.

Key words: Banff National Park, Canadian Forest Fire Danger Rating System, fire ecology, wildland fire, wildfire.

Résumé : La science des incendies forestiers a connu des progrès considérables au cours du dernier demi-siècle, avec des avancées dans tous les principaux domaines d'investigation. Dans cet article, nous célébrons le 50e anniversaire de la Revue canadienne de recherche forestière en réfléchissant à l'histoire de la recherche scientifique sur les incendies de forêt au Canada. Nous examinons l'évolution de cette science au cours des 50 dernières années au Canada, notamment pour les principaux développements et contributions dans la conception du système canadien d'évaluation des dangers d'incendie de forêt, la climatologie-météorologie des incendies, le changement climatique, l'écologie des incendies et la gestion opérationnelle des incendies. Nous présentons, à titre d'exemple, une étude de cas sur l'évolution de la gestion des incendies dans le parc national de Banff. Nous concluons en discutant des orientations des recherches futures sur les incendies de forêt au Canada, notamment pour ce qui est de l'évaluation future de la gravité des incendies et de leurs effets, de l'efficacité des traitements de gestion des combustibles et des effets du changement climatique, ainsi que du développement de l'analyse des risques d'incendie de meme que des modèles de comportement des incendies. Nous constatons également qu'il est toujours nécessaire de mieux intégrer la gestion des forêts et la restauration écologique à la réduction des risques d'incendie. Tout au long du document, nous faisons référence aux nombreuses contributions publiées dans le Canadian Journal of Forest Research, qui a été à la pointe de la science internationale en matière d'incendies de forêt.

Mots-clés : Parc National de Banff, Système canadien d'évaluation des dangers d'incendie, écologie, feux de forêts.

1. Introduction

Wildland fire has been a persistent feature of the Canadian landscape for millennia (Richard 1993; Price et al. 2013). On average, fires have burned 1.96 Mha per year in Canada from 1959 to 2015, and the annual area burned is trending upward (Hanes et al. 2019). The majority of burned area occurs in the boreal and taiga forests (Figure 1a, Stocks et al. 2003) due to a relatively small proportion of large fires (Hanes et al. 2019) that burn on comparatively few days of severe fire weather (Wang et al. 2017). Both lightning and people are the main ignition agents in Canada, accounting for roughly 50% of fires each (Stocks et al. 2003; Hanes et al. 2019; Coogan et al. 2020). Over the last half century in Canada, however, human-caused ignitions were responsible for ~10% of the area burned, whereas lightning was responsible for the remainder (Hanes et al. 2019). Furthermore, the seasonality of human- and lightning-caused fires differ, with human-caused fires occurring more often during spring and autumn, and lightning-caused fires occurring more often during the summer months (Figure 1b).

While Indigenous people have long used traditional knowledge of fire as a beneficial tool for landscape modification to support their subsistence lifestyle (Christianson 2015), formal scientific research of wildland fires in Canada began in the 1920s, with research agencies being established in 1960 (Pyne 2007). Prior to the 1970s, however, wildland fire research in Canada was impeded by a variety of factors, including deficient record keeping among jurisdictions (e.g., many provinces did not record fires in remote northern regions), while technological limitations and poor access to remote areas left many fires undocumented (Stocks et al. 2003; Tymstra et al. 2020). Following the 1970s, and continuing to the present, many significant developments occurred in the realm of Canadian wildland fire science that have had important impacts in Canada, and have influenced wildland fire science and management around the globe.

A major accomplishment of early wildland fire research was the development of the Canadian Forest Fire Danger Rating System (CFFDRS; Stocks et al. 1989), which includes as subsystems both the Fire Behaviour Prediction (FBP) System (FCFDG 1992; Wotton et al. 2009a) and the Fire Weather Index (FWI) System (Van Wagner 1987; Wotton 2009b). The

CFFDRS products are used to this day in operational fire management and constitute an important part of the fundamental working knowledge of wildland fire in Canada. Moreover, the Canadian FWI System is adaptable to different regions, and modified versions have been used in several countries around the world (Carvalho et al. 2008; de Groot et al 2015).

A key paradigm shift that has occurred within the last 50 years of wildland fire research in Canada has been the transition from relatively simplistic to more complex conceptual and computational models that offer more nuanced insights into fire effects, fire regimes, forest ecology, and their implications for forest management (Van Wagner 1978). Fire itself has been increasingly recognized as an important ecological process in Canadian forests, playing a key role in vegetation regeneration (De Grandpre et al. 1993), forest composition and heterogeneity (Bergeron and Dubuc 1989; Johnson 1992), soil nutrient dynamics (Thiffault et al. 2007), hydrology (Bladon et al. 2008), and carbon cycling (Amiro et al. 2001). As such, there has been a shift in fire management policy from full suppression towards an "appropriate response" strategy that facilitates flexibility in fire response decision making. Under such a strategy, fires may be intentionally left to burn under appropriate circumstances in order to promote their positive ecological effects (Hirsch et al. 2001; Tymstra 2020).

Over the past few decades, the potential and realized impacts of climate change have come to the forefront of scientific research, and present a significant challenge to the future of wildland fire in Canada (Flannigan and Van Wagner 1991; Coogan et al. 2019). Climate change is predicted to increase lightning ignitions (Krawchuk et al. 2009), the occurrence of more severe fire weather (Flannigan et al. 1998), fire season length (Jain et al. 2017), fire intensity (Wotton et al. 2017), area burned (Flannigan et al. 2005; Boulanger et al. 2014; Wang et al. 2020), emissions (Amiro et al. 2009), and both the occurrence and frequency (Wotton et al. 2010) of fires in many regions in Canada. Already, there is evidence that anthropogenically-driven climate change is impacting Canadian fire regimes (Gillett et al. 2004; Coogan et al. 2019). It is therefore not surprising that climate change effects are anticipated to continue to add to the burden of wildland fire management, which may become increasingly challenged over the coming decades (Flannigan et al. 2009a; Podur and Wotton 2010; Stocks and Martell 2016). Climate change thus presents formidable challenges that create an urgent need for innovative wildland fire science and management now and into the future.

In this paper, we celebrate the 50th anniversary of the Canadian Journal of Forest Research by reflecting on the considerable progress achieved in select areas of wildland fire science in Canada over the past half century. In particular, we discuss key developments and contributions in the creation of the Canadian Forest Fire Danger Rating System; the relationships between wildland fire and weather, climate, and climate change; fire ecology; operational fire management; and wildland fire management. We also present a case study of the evolution of wildland fire management in Banff National Park, Alberta. It should be noted that our review is not meant to be exhaustive, and that several important areas of Canadian wildland fire science have not been covered in our review. Such omissions should not be misconstrued as indicating insignificance, but rather as a reflection of the authors' expertise. Throughout the paper, we reference many contributions published in the Canadian Journal of Forest Research, which has been at the forefront of international wildland fire science. As in any well-developed discipline, much of the discussion below employs specific terminology (Table 1), with many of these terms and concepts since transferred from fire science to disturbance ecology in general (White and Pickett 1985).

2. The fire environment: weather and fire behaviour

2.1. Development of the FWI and FBP Systems and major milestones

Research into the linkages between weather and wildland fire began in Canada about 90 years ago with the intent to provide early warning about hazardous conditions to better prepare for fire and reduce the losses of both human life and timber; Van Wagner (1990) provides an extended summary of the development of fire research in Canada from 1930 to1990. Several fires in the early decades of the 20th century had not only burned large areas of timber, but also caused very significant losses of life in northern communities; for example, the Great Porcupine Fire (Timmins, Ontario) in 1911, the Matheson Fire (Black River-Matheson, Ontario) in 1916, and the Great Fire (Timiskaming, Ontario) of 1922. The aforementioned research, which began at what is now the Petawawa Research Forest in Ontario, expanded over a period of decades to include research stations across Canada (Paul 1969) and led to the development of the first sets of regional fire hazard tables and fire danger indices that were used by local fire management agencies in daily preparedness and response planning. These various regional systems were combined into the FWI System in 1970 and became Canada’s national fire danger rating system (Van Wagner 1974, 1987). The FWI System, largely in the form first laid out in 1970, is still used daily across Canada during the fire season and has been adapted to conditions in numerous other countries around the world to provide the foundation of wildland fire early warning systems (e.g., New Zealand, Indonesia, Malaysia, Costa Rica; de Groot et al. 2015).

The FWI System was (and still is) designed to provide relative information about the fire environment across districts or regions of the forest in general and is used as the main public communication tool regarding fire danger (e.g., through the common roadside signs of fire danger). Components of the FWI System are also used by fire management planners to inform their assumptions and predictions about potential daily fire occurrence and the growth potential of any fires that might occur or that are already burning on the landscape.

With the establishment and widespread adoption of the FWI System, Canadian fire behaviour research moved from its focus on small-scale ignition experimentation in the late 1960s and early 1970s to large plot burning in forest types across the country. This program, which was most active through the 1970s and 1980s, sought to link weather and forest fuels to expected fire behaviour (Alexander and Quintilio 1990). It was envisioned that this new fire behaviour system would complement the FWI System by providing the more detailed predictions needed for suppression scenario planning on actual burning fires as well as by those undertaking prescribed burns to enhance the prescription setting to allow for lower-risk prescribed burns. The goal was to develop refined models of fire behaviour that could provide fire managers quantitative and realistic predictions of key elements of fire behaviour such as expected spread rates, fuel consumption, and fireline intensity across a range of fuel types. This field research program saw experimental plots (typically 0.4 ha to 5.0 ha) burned under a range of weather conditions with the goal of capturing and documenting their effects on fire behaviour (see Text Box 1). This system, published as the FBP System (FCFDG 1992), has provided operational fire behaviour prediction capability to fire management throughout Canada and has been incorporated into *Prometheus*, Canada’s operational wildland fire growth model (Tymstra et al. 2010). The development of spatially explicit fire behaviour and growth models, such as Prometheus and BehavePlus (Andrews 2014), have aided real-time planning for the deployment of fire suppression resources within and among fires, especially when many large fires burned concurrently.

TEXT BOX 1: The development of the two major systems in the CFFDRS, the FWI System and the FBP System, is the accomplishment of no single person. The approach to fire behaviour research in Canada has relied upon extensive field-scale burning aimed at understanding the primary factors driving the process within actual fuel complexes representative of forest types across the country. This multi-decade field-intensive work has only been possible through a very active and lasting collaboration between numerous fire researchers and fire management agencies across the country (e.g., Wright 1932; Van Wagner 1963; Lawson 1973; Quintilio et al. 1977; Stocks 1987ab, 1989; Alexander et al. 1991). The experimental burning program represents a very significant investment in understanding fire behaviour within Canadian forests. The impact of each of these individuals and the long-lasting relationships between fire research and operations in Canada cannot be undervalued.

One significant architect of the modern system worth individual recognition is C. E. Van Wagner. Van Wagner used the basic physics of fuel heating and fire spread as the foundation of the CFFDRS's model forms. This approach captured the impacts of the primary drivers of fire spread or moisture exchange and formed the basic functional forms of the models used within the FWI and FBP Systems today. These model forms were then calibrated with observations collected during field campaigns resulting in models that had potential for use across a wide range of conditions and which also provided realistic quantitative predictions to operational users. **[TEXT BOX end]**

Fire across much of Canada's boreal forest is dominated by high-intensity crown fire. We have come to understand that such stand-replacing fires, seen a century ago as a threat to our personal well-being and economic development, are an important part of forest health in many biomes. However, understanding crown fire spread has been a critical feature of our ability to prepare for and manage unwanted fire within our managed forests. Van Wagner (1977) produced the first comprehensive conceptual framework for understanding both the initiation and sustainable spread of crown fires in boreal coniferous forests. These basic models are still used today to predict the escalation of surface fire into a spreading canopy fire in operational fire behavior prediction systems around the world (Andrews 2014; Opperman et al. 2006).

Arguably, the next great advancement in understanding crown fire behaviour came two decades later when the International Crown Fire Modelling Experiment (ICFME) provided a multi-year opportunity to study this important, extremely high-intensity phenomenon. That project, which is summarized in a 2004 special issue of the Canadian Journal of Forest Research (see Stocks et al. 2004), brought together >100 fire scientists from 14 different countries to study crown fires. The intensive research focus of the ICFME not only lead to an improved understanding of traditional aspects of fire behaviour (e.g., crown fire spread rates and crown fuel consumption) but also provided some of the first detailed characterizations of the flaming zone within an active crown fire (e.g., flame temperature, flame front residence time, flame radiant energy). Furthermore, the ICFME also produced some of the first field-based observations of structure ignition potential from crown fire (Cohen 2004); these observations have since been used to refine and validate models of structure ignition that have formed the foundation of safety zone size in the wildland-urban interface. Observations from the ICFME also provided validation data for new physically-based numerical models that couple fire and wind to allow more detailed investigations of the complex interactions that influence wildland fire behaviour (Linn et al 2012); such models continue to be used to augment existing observational evidence and explore important aspects in wildland fire management (Marshall et al. 2020).

From the operational fire management perspective, the last 50 years have seen advancements in understanding the stochastic nature of fire ignition, including the factors that influence the expected number of fires an agency might see arrive on any given day. Cunningham and Martell (1973) were among the first in Canada to show that the number of human-caused fires on any particular day could be predicted with the FWI System's outputs; however, their further observation that such arrivals could be modelled following a Poisson distribution allowed uncertainty to be estimated around these predictions. These concepts have been further developed in Canada (Martell et al. 1987, 1989; Vega-Garcia et al 1995; Wotton et al. 2011; Woolford et al. 2011; Nadim et al. 2020) and elsewhere. Information systems based on these original modelling concepts are used today in daily operational fire management planning to provide spatially detailed indications of where to expect ignitions each day (both human- and lightning-caused), as well as providing regional summaries of the expected number of new fire arrivals and associated uncertainty (summarized as prediction intervals) to assist in operational decision-making (Woolford et al. (submitted to this CJFR Special Issue)).

While many elements of the CFFDRS were initially focused on informing fire suppression operations planning, the emphasis on understanding the impacts of fire on the forest environment has grown. Furthermore, the models within the CFFDRS have been used in a variety of ways because the CFFDRS integrates sound linkages between weather, fuels, and fire behaviour. Van Wagner (1977) provided a framework that linked together the effects of underburning (and other surface fuel reduction techniques), pruning, and canopy thinning; these three elements are the cornerstones of modern fuel management approaches for risk reduction, particularly in the wildland-urban interface (Agee and Skinner 2005). Understanding the impacts of fuels and the potential for fuels reduction techniques to mitigate fire danger has become an area of greatly increased activity over the last few decades as land managers seek ways to adapt to, and coexist with, fire activity on the landscape (Stevens et al. 2012; Moritz et al 2014). Although commonly applied in montane forests of western North America, fuels management in crown-fire dominated boreal forests is a challenging balance between reducing crowning potential through fuel reduction (i.e., overstory thinning) without increasing surface fire intensity (through increased overall fuel dryness and increased surface wind). While the original fuel typing in the FBP System was not readily adaptable to studying the impact of fuels management on fire behaviour, a significant emphasis of the new generation of the FBP System (currently under development) will focus on a more structural definition of fuel complexes that allows users to consistently evaluate the effects of stand manipulations (Marshall et al. 2020).

As understanding the carbon budget of Canada's forests became increasingly of interest, the role of fire in terms of releasing CO_2 directly to the atmosphere could be explored directly with the fuel consumption models within the FBP System to provide the first detailed estimates of the contribution of fire in Canada's boreal forest to atmospheric greenhouse gas concentrations (Amiro et al. 2001). Through the late 1980s and 1990s, work on organic layer consumption in typical boreal fuels (e.g., Frandsen 1987, 1997; Miyanishi and Johnson 2002) has played a critical role in refining these atmospheric emission estimates from Canadian wildland fire. de Groot et al. (2007) developed modifications for the FBP System consumption models that allowed further refinement and fuel-load-specific projections of fuel consumption to be made for Canadian forests, further improving carbon emission results. Much of this earlier work was focused on upland forests; however, the more recent widespread recognition of the significant amount of carbon stored in peatlands, and the observation that this carbon can indeed be consumed in wildland fires, has in recent years led to increased research into the linkages between the conditions under which different peatlands can sustain fire and deep burning, and the potential carbon releases to the atmosphere (Turetsky et al. 2002, 2015).

2.2. Understanding the role of weather in wildland fire

One major advance in wildland fire science over the past 50 years has been the increased understanding of the role of weather—i.e., the state of the atmosphere at a particular time and place regarding temperature, precipitation, atmospheric moisture (e.g., relative humidity and vapour pressure deficit), wind, lightning, and other variables—in wildland fire dynamics. Wildland fire activity is strongly influenced by three factors: fuels, ignition agents, and weather (Flannigan et al. 2005). Research into these fundamental factors and their interactions have added greatly to the knowledge and management of wildland fires. For example, fuel amount, type, continuity, structure, and moisture content are critical elements for fire occurrence and spread. Weather—especially when hot, dry and windy—influences both the moisture content of fuels (and hence their receptivity to combustion) and also the spread of fire itself and is thus a critical factor in fire behaviour. In addition to being one of the three factors, weather is unique in that it also plays a role in the other two factors: weather causes ignitions due to lightning and affects fuel moisture. Regarding ignition agents, lightning-caused fires are responsible for proportionally more area burned in Canada because lightning can occur in remote areas where fire detection and suppression (if any) are often delayed compared to human-caused fires that usually occur in southern full-suppression zones. Additionally, lightning-caused fires can occur in large numbers over a short period of time which can overwhelm a fire management agency's capacity to respond. Recent research suggests that the number of lightning-caused fires have increased in some regions of northern and western Canada over the last 50 years (Hanes et al. 2019; Coogan et al. 2020).

Extreme conditions drive the wildland fire world. Most of the area burned in Canada has been attributed to a relatively small number of fires (~3% of fires are responsible for 97% of the area burned; Stocks et al. 2002), and recent research has demonstrated that most of these fires and associated area burned occurs on just a few critical days (i.e., “spread days”) with extreme fire weather (Podur and Wotton 2011; Wang et al. 2017). Furthermore, it has been demonstrated that such extreme fire weather episodes are frequently associated with cold fronts and blocking ridges (e.g., Petoukhov et al. 2018).

Weather is also arguably the best predictor of regional fire activity for monthly time periods or longer. For example, Cary et al. (2006) found that weather and climate best explained modelled-area-burned estimates from landscape fire models compared with variation in terrain and fuel pattern. Although wind speed may be the primary meteorological factor affecting fire growth of an individual fire, numerous studies suggest that temperature is the most important variable affecting overall annual wildland fire activity with warmer temperatures leading to increased fire activity (Gillett et al. 2004; Flannigan et al. 2005; Balshi et al. 2009; Parisien et al. 2011). The reasons for the positive relationship between temperature and regional wildland fire are three-fold. First, warmer temperatures increase evapotranspiration because the atmosphere's capacity to hold moisture increases rapidly as temperatures increase (Williams et al. 2015) which consequently lowers water table position and decreases forest floor and dead fuel moisture content unless precipitation is sufficient enough to offset the moisture loss (Flannigan et al. 2016). Second, warmer temperatures translate into greater lightning activity which generally leads to increased fire ignitions (Price and Rind 1994; Romps et al.2014). Third, warmer temperatures may lead to a lengthening of the fire season (Wotton and Flannigan 1993; Westerling et al. 2006; Flannigan et al. 2013; Jolly et al. 2015). While testing the sensitivity of landscape fire models to climate change and other factors, Cary et al. (2006) found that predicted area burned increased with higher temperatures even when precipitation increased; although, the increase in area burned was greatest for the warmer and drier scenario.

2.3. Wildland fire and climate change

Wildland fire scientists have for decades been leaders of climate change science, and they continue to actively research the potential and realized impacts of climate change on wildland fire activity. While weather indicates the local state of the atmosphere over a relatively brief period of time, climate represents the average weather characteristics of a particular region, or globally, over a period of many years (e.g., 30-year climate normals). Climate change is thus the long-term change in average weather patterns that define climates on local, regional, and global scales and has a broad range of effects. The potential impacts of climate change on wildland fire danger in Canadian forests have been studied for decades and are generally well understood (Flannigan and Van Wagner 1991; Stocks 1993; Stocks et al. 1998; Flannigan et al. 1998; Flannigan et al. 2000)—in fact, the strong linkage the CFFDRS provides between weather variables and wildland fire allowed for a seamless transition for looking at climate change impacts on fire in Canada. This understanding is rooted in the linkage between weather, fuel drying, and the subsequent ignition and spread of fire within wildland fuels—all processes that have been the subject of study since the beginnings of modern wildland fire research (Gisborne 1923; Wright 1932; McArthur 1966; Van Wagner 1968; Van Wagner 1977; Anderson et al. 1970; Rothermel 1972).

Studies of the potential impacts of climate change on the area burned in North America's boreal forest have projected increased disturbance levels through the current century (Flannigan et al. 2005; Balshi et al. 2009). As a result of increased wildland fire burning, Amiro et al. (2009) projected a doubling of wildland fire greenhouse gas emissions in Canada by the end of this century using the Canadian Global Circulation Model (CGCM1). The projected increases were largely due to increases in area burned and not due to increases in the depth of burn. Recent research, using three different General Circulation Models (GCMs; HadGEM2, CanESM2, and CSIRO-MK3.6.0) and three Representative Concentration Pathway (RCP) scenarios (2.6, 4.5, and 8.5), however, suggested that the proportion of days in the fire season with the potential for significant forest floor fuel consumption (including depth of burn) by fire will increase across Canada's forests, more than doubling for British Columbia (BC) and the rest of the boreal forest by 2100 (Wotton et al. 2017). The doubling of fuel consumption due only to depth of burn by fire may occur as early as the 2030s in BC.

Already, we have seen indications of climate change effects on Canadian fire regimes. There have been increases in area burned and fire season lengths in western and northern Canada (Coogan et al. 2020; Hanes et al. 2019) where warming has been the greatest. For example, interior BC, Alberta, and northern Ontario have longer fire seasons today as compared to 1959-2000 (Albert-Green et al. 2013; Hanes et al. 2019). Gillett et al. (2004) suggested that the increase in area burned in Canada over the past four decades was due to human-caused increases in temperatures. Recent research suggests that the frequency of extreme burning conditions in western Canada during the last decade increased by 1.5 to 6 times due to climate change (Kirchmeier-Young et al. 2017). Kirchmeier-Young et al. (2019) suggested that anthropogenic climate change increased the area burned by a factor of 7 to 11 times during extreme fire seasons (e.g., the 2017 fire season in BC). Such observed increases in fire activity, including large and high-intensity fires, are consistent with climate change projections (Flannigan et al. 2009b; Hanes et al. 2019).

While the level of absolute change in fire activity may be uncertain, particularly since many studies do not consider increases in lightning activity (Romps et al. 2014), overall it seems clear that, barring very significant changes in forest composition, fire activity in the boreal forest will in the future continue to increase with climate change. Several studies have projected ignition increases due to decreased fuel moisture driven by the changing climate (Wotton et al. 2003; Wotton et al. 2005; Wotton et al. 2010; Podur and Wotton 2010). While all GCM projections indicate considerable spatial and temporal variability in changes in summertime rainfall amounts (both increases and decreases), it has been demonstrated that increases in fuel moisture due to projected increases in rainfall are more than offset by increased evapotranspiration from fuels on and in the forest floor (Flannigan et al. 2016).

Given the exacerbating effects (both observed and anticipated) of climate change on wildland fire activity in certain areas of Canada, it is not surprising that climate change is expected to severely challenge wildland fire management agencies. While Canada has experienced increased area burned, similar observations have been made in the western US since 1984 (Dennison et al. 2014). Importantly, such increases in area burned in both Canada and the western US have occurred despite stable or increasing fire suppression effectiveness and increased coverage by fire suppression resources. Wotton et al. (2005) used an initial attack simulation model to examine changes in escaped fires under future fire-weather scenarios and concluded that the non-linear relationship between escaped fires and fire occurrence is likely to overwhelm fire control capacity. Wotton et al. (2017) suggest that the proportion of days with high-intensity fires that are difficult or impossible to extinguish will increase by 2 to 3 times for BC and the boreal forest by 2100.

3. Fire regimes and forest dynamics

Fire is arguably the most important global agent of ecological disturbance (Bowman et al. 2009) and is responsible for the dynamics, biodiversity, and productivity of many of Canada’s ecosystems. Advances in fire ecology originated in the 1970s and were catalyzed by three major paradigm shifts in the broader discipline of ecology (Pickett and White 1985; Glenn-Lewin et al. 1992; Turner 2010). (1) disturbance is now recognized as pervasive, rather than an exception or rare disruptor of stable ecosystems, and fire is acknowledged as essential for many ecosystems to function. (2) disturbances are diverse, with stochastic elements making them unpredictable. Individual fires vary in magnitude, altering the state and trajectory of ecosystems and driving temporal change and spatial heterogeneity among patches. Collectively, fires form complex regimes that vary among ecosystems and through time. (3) Human influences are ubiquitous and important drivers of ecosystem change, including Indigenous cultural fire that has been part of ecosystem dynamics for millennia. Paralleling the paradigm shifts in theory, research into the ecological aspects of fire regimes and fire influences on forest dynamics has grown rapidly in

Canada. Given its ecosystem-specific nature, research on fire ecology has been undertaken at regional scales, and diverse research approaches have been employed to decipher complexity across a range of spatial and temporal scales (Figure 2).

3.1. Fire regime characterization

Fire regimes vary tremendously across Canada's diverse forests and through time. The pioneering works by Heinselman (1973), Cywnar (1977, 1978), and Van Wagner (1978) inspired early research on fire regimes in Canada. Initially, the fire cycle was considered the primary distinguishing attribute of fire regimes, focusing on large crown fires that accounted for the majority of area burned, especially in boreal forests. Van Wagner (1978) introduced the concept of the fire cycle and the analytical methods to quantify fire frequency from forest age distributions at landscape scales (Johnson and Van Wagner 1985; Johnson and Gutsell 1994). Van Wagner's classical approach was widely applied to characterize fire in boreal and montane forests across Canada (e.g., the Maritimes (Wein and Moore 1977), Québec (Payette et al. 1989), and the Rocky Mountains (Tande 1979)) revealing tremendous spatial variation across well-documented environmental gradients. For example, extensive research in eastern boreal forests has revealed that historical fire cycles generally increased from several decades to centuries along dry-to-wet precipitation gradients (Foster 1983; Bergeron et al. 2001, 2004, 2006; Dobryshev et al. 2017) and along north-to-south temperature and drought gradients (Portier et al. 2016). At local scales, fire cycles are longer in wetlands and near water bodies (Senici et al. 2010; Erni et al. 2017) than on well-drained sites (Mansuy et al. 2010; Belisle et al. 2016). In forests of the Western Cordillera, historical fire cycles are longer on windward relative to lee sides of mountain ranges (Johnson and Larsen 1991; Van Wagner et al. 2006). In the cool wet temperate rainforests of coastal BC, fire cycles range from centuries to millennia, depending on topographic position and aspect (Lertzman et al. 2002; Gavin et al. 2003).

In addition to spatial variability in fire regimes, paleoecological reconstructions from charcoal, fossil pollen, and plant macrofossils in lake sediments, peat, and soil provided evidence of temporal instability throughout the Holocene (Senici et al. 2013; Remy et al. 2018). Many paleoecological studies conducted across Canada showed that the cool climate during the Little Ice Age resulted in relatively few fires and long fire return intervals, while fires burned at shorter intervals during the Holocene Thermal Maximum and the Medieval Warm Period (Hallett and Walker 2000; Lucas and Lacourse 2013; Prince et al. 2018; Girardin et al. 2019). However, important regional differences illustrated the need for ecosystem-specific knowledge of fire regimes and their variability. For example, humid conditions in the Western Cordillera during the Holocene Thermal Maximum yielded less frequent fires (Hallett et al. 2003; Hoffman et al. 2016; Brown et al. 2017, 2019), while fire declined during the Medieval Warm Period along the moisture-limited prairie-forest ecotone due to shifts in species composition to less fire-prone species (Campbell and Campbell 2000). Recent analyses have documented ecologically meaningful human influences on fire regimes over centuries to millennia (Blarquez et al. 2018; Hoffman et al. 2016, 2017; Murphy et al. 2019).

Researchers also began to identify and understand that there was an increasing trend in the length of fire cycles in Canadian forests starting in the mid-1700s (Johnson and Larsen 1991; Van Wagner et al. 2006), which became widespread across Canada in the mid-1800s to early 1900s (Bergeron 1998; Weir et al. 2000; Van Wagner et al. 2006; Lauzon et al. 2007). These fire cycle increases were commonly attributed to a warmer but moister climate that became less conducive to large fires at the end of the Little Ice Age, depending upon the region (Johnson and Larson 1991; Bergeron and Archambault 1993; Flannigan et al. 1998; Weir et al. 2000; Lefort et al. 2003; Bergeron et al. 2006; Girardin and Wotton 2009). In addition to climatic variation and change, other important factors driving fire regime shifts were identified including disruptions to Indigenous cultural use of fire (Lewis 1978; Pellatt and Gedalof 2014; Lake and Christianson 2019), land-use change following European colonization (Weir et al. 2000; Grenier et al. 2005; Marcoux et al. 2015), and modern fire suppression (Grenier et al. 2005; Chavardes et al. 2018). Altogether, biophysical factors and human impacts explained the widespread elongation of fire cycles starting in the mid-1900s.

An emergent theme across Canadian forests is the recognition that fire has diverse effects on ecosystems and that assuming high-severity fires and even-aged forests dominate across forest types is an over-simplification. Over the past 20 years, fire ecology research shifted from focusing strongly on the fire cycle to an improved understanding of variation among fire regimes and a more nuanced understanding of fire interactions with complex stand and landscape dynamics (Heyerdahl et al. 2012; Boulanger et al. 2014; Marcoux et al. 2015). Despite the importance of fire in boreal forests, long fire-free intervals and evidence of variable fire effects contrasted the traditional model of repeat high-severity fires forming a landscape mosaic of even-aged forests (Gauthier et al. 2009). Even in boreal forests, time since fire was often long enough to allow changes in tree species composition and forest structure over time (Bergeron et al. 1999, 2001, 2002). With longer fire cycles, a larger proportion of the landscape approaches the late successional stages of forest development, maintaining unique old-growth structures at stand-to-landscape scales (Cyr et al. 2010; Bergeron et al. 2017). Similarly, assessment of burn mosaics within contemporary fires revealed complex spatial patterns thereby refuting the implicit assumption that >80% of trees are killed in most boreal forest fires (Van Wagner 1983; Kafka et al. 2001; Burton et al. 2008). Detailed assessment of aerial photographs and remotely sensed data also showed important variation in fire severity (Boucher et al. 2017; Whitman et al. 2018a; Guindon et al. in press) and abundant residual structures including individual trees, island remnants, persistent fire refugia, and convoluted fire boundaries (Andison 2012; Krawchuk et al. 2016). Areas of lower-severity fire effects were found to reflect topo-edaphic characteristics (e.g., elevation, aspect, terrain ruggedness, distance to waterbodies) modulated by fire weather (Andison and McCleary 2014; Krawchuk et al. 2016; Rogeau et al. 2018; Whitman et al. 2018a) as well as forest age, composition, and presence of organic soils (Kafka et al. 2001; Ouarmim et al. 2015). Collectively, these studies refuted the concept of stable or steady-state landscapes (Cumming et al. 1996), a concept replaced by an improved understanding of, and research methods to address, episodic fires that drive temporal instability in long-term records and spatial variation within landscapes (Reed et al. 1998; Reed 2006; Cyr et al. 2016; Rogeau and Armstrong 2017).

Indigenous ecological knowledge (Turner et al. 2000; Lewis et al. 2018; Lake and Christianson 2019), combined with historical documents (Bjorkman and Velland 2010; Terrail et al. 2020), and repeat aerial and oblique photographs (Rhemtulla et al. 2002; Bergeron et al. 2004; Stockdale et al. 2019) have independently corroborated and refined interpretations of historical fire regimes in Canadian montane forests. In the forests of the Western Cordillera, historical fire regimes varied across mountain ranges, along latitudinal and elevational gradients, and by topographic position (Heyerdahl et al. 2007; Rogeau et al. 2016; Rogeau and Armstrong 2017). In these complex biophysical environments, historical mixed-severity fire regimes included low-, moderate- and high-severity effects within individual fires and among fires through time. In contrast to high-severity fires, the majority of trees survive frequent, lower-severity surface fires in which fire-resistant, thick-barked trees form cambial scars (Amoroso et al. 2011; Heyerdahl et al. 2012; Marcoux et al. 2015; Harvey et al. 2017). In the mixed-conifer valley-bottom and montane forests, mixed-severity fire regimes include frequent surface fire at lower elevations, transitioning to infrequent crown fires at higher elevations (Heyerdahl et al. 2007, 2012; Marcoux et al. 2013, 2015; Chavardès and Daniels 2016; Greene and Daniels 2017). Widespread crown fires commonly yield even-aged subalpine forests dominated by early-successional species (e.g., lodgepole pine, *Pinus contorta*), although trees with multiple fire-scars indicate some mixed-severity effects, while persistent fire refugia and forests with complex structures and old trees indicate long fire-return intervals in mesic climates (Mustaphi and Pisaric 2013; Marcoux et al. 2015; Rogeau and Armstrong 2017; Rogeau et al. 2018).

A striking temporal pattern in montane forests, where historically mixed-severity fire regimes prevailed, was the virtual elimination of surface fires starting in the late 19th century in southern BC (Marcoux et al. 2015; Greene and Daniels 2017; Harvey et al. 2017) and the foothills of Alberta (Amoroso et al. 2011; Rogeau et al. 2016, 2018). Although multi-decadal climatic variation resulted in cool wet periods, there were periods when climate was conducive to fire during which human influences explain fire deficits (e.g., Chavardes et al. 2018). Displacement of Indigenous people from their traditional territories and criminalization of their cultural burning practices eliminated human-ignited surface fires from many western forests (Lewis 1978; Lewis and Ferguson 1988; Lake and Christiansen 2019). The effects of European colonization (due to mining, agriculture, livestock grazing, and logging) altered forest fuels and excluded fire, while at the same time fire suppression became increasingly effective (Hessburg et al. 2019). Consequent changes in montane forests included the dense growth of ladder fuels, dead wood surface fuel accumulation within stands (Marcoux et al. 2015; Chavardes and Daniels 2016), and shifts to closed-canopy forests of fire-intolerant species that homogenized fuels along elevational gradients (Rhemtulla et al. 2002; Chavardes and Daniels 2016; Rogeau et al. 2016; Stockdale et al. 2016, 2019). In essence, trees, stands, and landscapes in many montane forests have become increasingly vulnerable to burning during intense crown fires; a situation further exacerbated by climatic change (Hessburg et al. 2019; Daniels et al. 2020).

3.2. Fire and forest dynamics

Conceptual models of forest succession and development are integrally linked to our understanding of disturbance. In the classical interpretation of the role of fire in Canadian boreal forests, high-intensity crown fires were understood to reduce the inhibitory influences of trees, shrubs, herbs, and forest floors in proportion to fire severity (Johnson 1992). With shading and other forms of competition reduced, a flush of nutrients released through combustion, and the forest floor reduced or mineral soil exposed, plant community succession and even-aged forest development are initiated and were understood to proceed along predictable pathways (Kimmins 1987). However, research over the last 30 years has shown that post-fire dynamics in Canadian forests are more diverse and complex than this classical model implies.

Recognizing that species respond to disturbances differently, Rowe (1983) adapted Noble and Slatyer's (1980) classification of plant life history attributes (termed "vital attributes") to represent the range of boreal species adaptations to fire size, severity, and frequency. After high-intensity crown fires, for example, "invaders" with highly dispersive seeds, "endurers" that resprout from subsurface perennating buds, and "evaders" that store seed in the soil or canopy

(Rowe 1983) colonize and grow rapidly in open conditions (Johnson et al. 2003). Often these early-successional, post-fire species are shade intolerant and their populations are perpetuated by recurrent fires burning at intervals shorter than the average tree lifespan, creating cyclical patterns of succession (Johnson 1992; Chen and Popadiouk 2002; Brassard and Chen 2006). Far from being uniform, tree regeneration following large, intense fires can be constrained by dispersal limitations from unburned forest (Galipeau et al. 1997; Greene and Johnson 2000), and burn severity affecting forest floor thickness influences seedling growth and survival during subsequent growing season droughts (Greene et al. 2004, 2007). Given the interactions of species traits and regeneration dynamics with fire regimes (Bergeron and Dubuc 1989; Bergeron and Dansereau 1993), modulated by edaphic and climatic conditions (Gauthier et al. 2000; Brassard and Chen 2006), post-fire species composition and forest structure can be much more complex than visualized 50 years ago.

Rowe (1983) also introduced species classified as “avoiders” in his vegetation disturbance framework. During relatively long fire-free intervals, forests mature and shade- and fire-intolerant “avoider” species gradually establish and dominate, as per classical succession theory (Rowe 1983; Oliver and Larson 1996; Franklin et al. 2002). In general, the mid- and late-successional avoiders are shade-tolerant coniferous species, such as white cedar (*Thuja occidentalis*), balsam fir (*Abies balsamea*), subalpine fir (*Abies lasiocarpa*), or white spruce (*Picea glauca*), that dominate in mesic climates or on poorly-drained sites that are less conducive to high-intensity fires (Bergeron and Dubuc 1989; Brassard and Chen 2006). In the absence of fire over periods of one or more centuries, low-to-moderate severity disturbances such as defoliation or treefall following insect attack, root rot, or wind storms, create small gaps within stands and initiate regeneration beneath the existing canopy (Lewis and Lindgren 2000; Parker et al. 2006). Such disturbances, in turn, can alter the fuel characteristics and fire behaviour of affected forests (Stocks 1987b; Perrakis et al. 2014). Where broadleaved deciduous species dominate immediately following fire, the establishment of coniferous avoiders initiates a transition to mixedwood stands. Under some conditions, avoiders may establish immediately following fire, if seed sources are available. Relative to the dominant invader, evader, and endurer species, shade-tolerant avoiders may grow slowly and recruit to the upper canopy only after the death of canopy-dominant pioneer trees (Bergeron 2000; Chen and Popadiouk 2002; Amoroso et al. 2011; Chavardès and Daniels 2016). In other words, multiple disturbance agents and gap dynamics interact with fire regimes and are now known to be widespread in Canadian forests. These interactions make up distinctive disturbance regimes (e.g., Burton and Boulanger 2018) that yield a multi-scaled mosaic of forests dominated by different species, structures, and stages of development across environmental gradients, collectively contributing to dynamic, biodiverse forests.

Contrary to earlier assumptions that long periods without fires were all that was needed to support forests with large old trees, scientists now understand the importance of an alternative process pathway that depends on high-frequency but low-severity fires. Low-to-moderate intensity surface fires dominate in western montane forests (Daniels et al. 2017), the southern boreal zone, and on islands in eastern Canada (Bergeron 1991). In these fire regimes, Rowe's (1983) "resister" species, such as thick-barked mature Douglas-fir (*Pseudotsuga menziesii)*, ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), or red pine (*Pinus resinosa*), survive fire and recruit from seed (Bergeron and Brisson 1990; Marcoux et al. 2015; Chavardès and Daniels 2016). While the role of thick bark in species had been widely recognized as providing fire resistance, the role of surface fires in maintaining the overall health, diversity, and productivity of woodlands dominated by those tree species became appreciated only in recent decades (Perry et al. 2011; Hessburg et al. 2019). In the dry forest of BC, for instance, the frequent recurrence of low-severity fires creates stands that have escaped high-severity disturbance for many centuries, yielding old-growth forests.

Extreme fires in the past decade have raised concerns that the ecological resilience of forests have been jeopardized by climate change superimposed on cumulative human impacts (Stevens-Rumann et al. 2018; Hessburg et al. 2019; Coop et al. 2020). When the historic range of variation of fire regimes and forest dynamics have been exceeded, species and ecosystems are unable to resist or recover from disturbance (Johnstone et al. 2016). For example, Payette and collaborators (Payette et al. 2000; Simard and Payette 2005) have shown that outbreaks of spruce budworm (*Choristoneura fumiferana*) followed closely by intense fire may exceed the resilience of black spruce (*Picea mariana*), shifting closed-canopy forests to open woodlands. Similarly, reburns, or successive fires at short intervals, in boreal forests can irreparably damage soils and drive shifts in forest composition and structure (Girard et al. 2009, 2011; Whitman et al. 2018b, 2019). The probability of post-fire tree regeneration failure is expected to increase across forests types in the future with the projected increase in fire activity, warm temperatures, and drought (Whitman et al. 2018b; Splawinski et al. 2019; Boucher et al. 2020).

3.3. Reciprocal wildland fire and forest management

Wildland fire is unique among natural disasters affecting Canadian society (Tymstra et al. 2020). Wildland fire can threaten human lives and damage economically valuable resources, but is a vital process essential for ecosystem function. This juxtaposition adds complexity and challenges when simultaneously managing forests and fire.

Forest and fire management are integrally linked through their reciprocal influences on fuels, fire hazard, fire behaviour, and area burned. For much of the 20th century, economic development of forests promoted even-aged silvicultural systems as a substitute for stand-replacing fires in many Canadian forests. To sustain timber yield and economic rotations of 80 to 100 years (e.g., perceived cycles of crown fires), conifer species are planted at high density to regenerate forests on commercially-managed lands. Thus, legacies of past (and ongoing) forest harvesting and silvicultural practices are expressed in the composition and structure of current forests (Andison 1998; Friedman and Reich 2005; Sass et al. 2018) and determine fuel attributes and distribution at stand to landscape scales that affect fire behaviour (Lezberg et al. 2008). Less appreciated are the long-term effects of species choice, particularly the preference for conifers over broadleaf species, and its impact on fuel complexes by increasing landscape vulnerability to fire initiation and spread (Cumming 2001).

From an economic perspective, wildland fire competes with timber harvesting over much of the managed forest, causing significant uncertainty and disruption when determining sustainable harvest levels. Thus, fire suppression is strongly linked to forest management, and compelling evidence shows fire suppression reduces the area burned in intensively managed and protected forest zones in Canada (Martell 1994; Cumming 2005; Podur and Martell 2007). Recent research takes advantage of long documentary fire records, spatially-explicit remotely-sensed data, and increasingly sophisticated modelling to collectively show the direct impacts of aggressive fire suppression and indirect impacts of human modifications of the physical environment on the size, frequency, and seasonality of boreal fires (Martell and Sun 2008;

Pickell et al. 2016; Campos-Ruiz et al. 2018). Much progress has been made to assess a priori and a posteriori considerations when defining sustainable harvest levels under different fire regimes (Reed and Errico 1986; Boychuk and Martell 1996; Savage et al. 2013; Leduc et al. 2015). For example, integrated forest and fire management models address complex questions and trade-offs among fire protection, timber production, and old forest conservation, yielding potential net benefits of fire management (Rijal et al. 2018). Salvage logging after fire is an alternate solution that has increased considerably to compensate for the loss of timber (Nappi et al. 2004; Saint-Germain and Greene 2009), but with negative consequences to biodiversity (Schmiegelow et al. 2006; Lindenmayer et al. 2012; Thorn et al. 2018). Projecting forward, simulations suggest that it will become even more difficult to maintain current timber harvesting levels in the future under a warmer climate and with projected increases in area burned (Gauthier et al. 2015). Compounding this problem, an emerging consequence of successful fire suppression is increased flammability of the fuel in the wildland-urban interface of communities across Canada (Parisien et al. 2020).

Closer integration of forest and fire management is essential given their interdependencies and has become increasingly urgent as the cumulative effects of industrial forestry and fire on forested landscape biodiversity and productivity become evident. An important advance near the end of the 20th century was the widespread adoption of ecosystem-based forest management as a new paradigm for sustainability, which places greater emphasis on maintaining non-timber values and ecological integrity (CCFM 1995). In this framework, historical disturbance regime attributes provide reference conditions for ecosystem-based silviculture and ecological restoration (Long 2009), with fire regimes dominating many Canadian forests (Burton et al. 2003; Stockdale et al. 2016; but see Daniels and Gray 2006 for an exception). For example, inspired by research on spatial patterns of fire skips (Eberhart and Woodard 1987; Kafka et al. 2001), stand-scale retention of living trees in variable densities and distributions during forest harvesting is now incorporated in ecosystem-based management widely practiced in the boreal forests of Canada (Burton et al. 2006; Bergeron et al. 2002) and internationally (Gustafsson et al. 2012). However, creating landscape-scale spatial patterns consistent within the historical variation resulting from fire has proven more challenging (Andison and Marshall 1999; Pickell et al. 2013; Boucher et al. 2015).

Most recently, forest and fire management have shifted to emphasize resilience—i.e., the capacity of an ecosystem to return to the same general structure, composition, and feedback processes following disturbance (Holling 1973; McWethy et al. 2019; Sankey 2018). In this context, management to reduce fire risk and hazard across a range of scales is essential for long-term sustainability of forest ecosystem function and resource management. At stand scales, uneven-aged silvicultural systems traditionally used to promote tree growth and enhance wildlife habitat are being renewed as fuel mitigation treatments to reduce wildland fire risk (Agee and Skinner 2005). Particular emphasis is placed on the wildland-urban interface, where treatments tailored to specific forest types have potential local benefits (Johnston and Flannigan 2018; Beverly et al. 2020). At landscape scales, strategic location and configuration of fuel treatments aim to modify fire behaviour and mitigation of the wildland-urban interface (Finney 2001; Parisien et al. 2007). Across spatial scales, proactive measures include modifying forest operations and increasing prescribed burning to reduce hazardous logging residuals (Weber and Taylor 1992) and regenerating forests that include deciduous species to mitigate fire hazard (Girardin and Terrier 2015). Importantly, the growing recognition of the ecological benefits of fire has enabled the use of managed wildland fire, in which fires that do not threaten lives or critical infrastructure are permitted to burn within predetermined boundaries for beneficial ecological effects and cost management (Hirsch et al. 2001; Tymstra et al. 2020).

4. Decision support for operational fire management

Wildland fire suppression remains a critical component of contemporary fire management. Decision-making in operational fire management is an important subject area as alternative courses of action can affect costs and losses in the thousands to millions of dollars per fire and affect public and worker health and safety. Decision-making in operational fire management is largely expertise-based and for good reason: the decision environment is complex, highly variable, beset with rapid changes and uncertainties, and has become increasingly unprecedented. “Operational research” (OR)—the use of scientific and mathematical methods to aid decision-making—continues to support many levels and aspects of operational fire management. For example, risk assessment, which is widely used in operational fire management planning and procedures, can be interpreted as a practical simplification of decision analysis, a branch of OR. Martell (1982), Minas et al. (2012), Duff and Tolhurst (2015), and Martell (2015) give comprehensive reviews of the application of OR in fire management, which encompasses many areas including level of protection, capacity planning, aircraft selection, home basing, fire prevention, fuel treatment, detection, deployment, dispatch, travel, initial attack, suppression, large fire management, impacts, climate change analysis and interactions among fire management, wildlands, and forestry. Here, we highlight examples of OR over the decades to illustrate some of the impact and range of possibilities of this subdiscipline.

Modelling and analysis have been used to aid many long-term decisions. Quintilio and Anderson (1976) compared the effectiveness and cost of six different types of suppression resources by developing an initial attack simulation model. Simard (1979) developed *AIRPRO*, a very detailed fire suppression simulation model that compared airtankers by effectiveness, cost, and fire loss. Elements of these and other models were the basis for Martell et al.'s (1984) initial attack simulation model that represented the dispatch, queuing, suppression effectiveness, and cost of crews, helicopters, and fleets of mixed airtanker types. That analysis led to Ontario's and Canada's purchase of nine CL-215 airtankers for Ontario. That model was later expanded in stages to become *Leopards* (McAlpine and Hirsch 1999), which was used to support many of Ontario's decisions on capacity, level of protection, and system configuration. A version of the Leopards model was also adapted for application in British Columbia, where it was used to help evaluate alternative airtanker fleet configurations.

Regarding support for seasonal and daily decisions, MacLellan and Martell (1996) developed a mathematical programming model to help identify optimal home bases for Ontario's CL-215 airtanker fleet. The analysis led to changed home-basing by subseason. Hodgson and Newstead (1978) formulated and compared alternative coverage models for optimal tactical daily assignment of airtankers to bases in Alberta. Islam and Martell (1998) formulated a multi-base airtanker queueing model to aid tactical daily deployment decisions and to generate insights to guide dispatch policies to improve system performance. A software application is currently pending field testing in Ontario.

Ground-breaking optimization modelling is emerging with respect to tactical management of large fires using mixed-integer programming. Belval et al. (2015) formulated a model that represents dynamic fire growth interacting with spatio-temporally assigned suppression resources. Moreover, van der Merwe et al. (2015) developed such a model for the challenging, time-constrained problem of protecting assets in advance of large fires. The model considers various vehicle types, asset locations on a road network, and travel and protection-work times.

Despite the early work and ongoing successes, the use of operational research to support operational fire management has significant unrealized potential. The causes may include the limited number of those researchers specializing in fire management and the extra effort for, and obstacles to, collaborative work between researchers and operational decision-makers. Long-standing advice for ensuring the relevance and application of operational research is that researchers and decision-makers work together closely during all stages, from problem identification through implementation to ongoing evaluation (Martell 1982). Future progress is promising because of this recognition and the stated need "… to create and improve innovative fire management solutions and to assist in decision-making, so that fire response will be faster, safer, more effective, and more efficient" (Sankey 2018).

5. Banff National Park: a case study on innovative wildland fire management

As discussed throughout this paper, many significant developments in Canadian wildland fire science and management have occurred over the past fifty years. In this section, we highlight how some of this knowledge has been integrated and applied by fire managers by discussing the history and evolution of wildland fire management in Banff National Park (hereafter Banff), Alberta. Banff serves as an exemplar case study because it is Canada's first National Park (created in 1885) and there is a long history of fire use by humans in the region. In current times, millions of people visit and travel through the Park every year. As such, maintaining Banff's ecological integrity, including through the use of fire, is one of Parks Canada's key mandates.

Banff is located in the Rocky Mountains east of the Continental Divide within the present day territories of First Nations Treaties six, seven, and eight as well as the Métis Homeland. The park covers 6,641 km^2 in the Montane Cordillera Ecozone and includes three primary ecoregions: montane, subalpine (lower and upper), and alpine. Renowned for its natural beauty and wildlife, Banff contains a diverse range of flora and fauna due in large part to the range in elevation and diverse climates found in the Park. Importantly, the vegetated ecosystems of Banff have also been shaped by fire (Tande 1979; Johnson and Larsen 1991; Walker and Hallet 2001; Hallet and Hills 2006; Van Wagner et al. 2006). Banff's fire regime is characterized by infrequent lightning-caused fires during the summer season (July-August; Wierzchowski et al. 2002), with evidence from fire-history studies indicating that numerous fires have also occurred during the shoulder seasons (i.e., spring and autumn) which correlates with a long history of cultural burning by local Indigenous people and later by European colonists (Tande 1979; Hawkes 1979; Johnson 1987; Masters 1990; Rogeau 1994a,b; Rogeau and Gilbride 1994; Kubian 2013). In upper subalpine regions, however, the fire regime is dominated by low-frequency, mixed- and high-severity, lightning-caused fires.

Evidence from over 400 known Indigenous archeological sites suggests that humans have inhabited or travelled through the Banff region for nearly 11,000 years. There is also evidence of past Indigenous cultural burning at lower elevations in the Park based on regional ethnography and the historical prevalence of frequent low-intensity burning during the dormant season. This cultural burning was likely used as a tool by the Indigenous people for such things as the maintenance of travel corridors and wildlife habitat, and the supply of food and medicinal plants

(White 1985; Lewis and Ferguson 1988; Heitzmann 2009; Kay et al. 1999). However, with the establishment of the Canadian mountain national parks from 1885 onward, local Indigenous peoples were removed from the region thereby eliminating their burning practices. Banff's new colonists, and the railway, maintained fire on the landscape, albeit largely accidentally (White 1985; Van Wagner et al. 2006), until the dawn of effective fire control and prevention, after which open vegetation patterns began infilling with dense tracts of lodgepole pine and other coniferous species (Trant et al. 2020).

Fire suppression throughout the mid-20th century led to a significant decrease in fire in Banff and surrounding area (Figure 3) resulting in negligible area burned until the late 1980s. In that period of fire exclusion, however, a rare fire (i.e., the 1968 Vermillion Pass Fire) spread into Banff (Chernoff 2002). Importantly, the subsequent vegetation recovery monitoring that occurred after this fire led to a shift in the prevailing perception of fire as an agent of destructive change to the understanding of fire as a natural ecosystem process (Dube 1976; Harris 1976). By recognizing the ecological role of fire in fire-dependent ecosystems such as Banff, Van Wagner and Methven (1980) triggered fire history and fire regime research to determine the appropriate strategy for the restoration of fire on the fire-suppressed landscape. Moreover, it was recognized that practices such as fire exclusion and artificial vegetation renewal (i.e., logging) alone were unlikely to sustain Banff's ecological integrity to the same degree as fire restoration (McRae et al. 2001). Thus, Banff fire managers chose to use fire as the main landscape management tool and implemented the Park's first prescribed fire in 1983. On the heels of that first experimental burn came a rapid evolution in Parks Canada science and policy related to the requirements for fire management and fire use in Banff and other National Parks (Parks Canada 1986, 1989).

Another important study in Banff's history occurred in 1996, when the Bow Valley Study verified that fire exclusion had significantly impacted the montane and lower-subalpine vegetation communities (e.g., lower diversity, wildlife habitat loss) thereby indicating that natural processes such as fire needed to be restored to the ecosystem to maintain ecological integrity (Page et al. 1996). Furthermore, concurrent examination of the trophic interactions between wolves (*Canis lupus*), elk (*Cervus elaphus*), aspen (*Populus tremuloides*), and humans that occurred during the Bow Valley Study led to a better understanding of the interrelated effects of predation, herbivory, fire disturbances, and vegetation dynamics in the area (White et al. 1998). Shortly thereafter the Banff National Park management plan (Parks Canada 1997) introduced the goal of restoring 50% of the historic fire cycle annually (~1,400 ha) through a combination of both prescribed fire and wildfire (Figure 3). Throughout the 1990s fire managers in Banff implemented prescribed fire at an increasing rate and scale using the latest developments in fire behavior and fire effects science. In many locations initial prescribed fire applications in Banff burned homogeneous and dense stands of mature lodgepole pine that were typical of many western Canadian forests following fire exclusion—these forests burned with high enough intensity to result in significant canopy mortality and started the process of restoring more open forest types.

Another important contribution to fire management in Canada occurred in the 2003 Fairholme prescribed fire (hereafter Fairholme) which was in part undertaken to manage mountain pine beetle (*Dendroctonus ponderosae*) populations and habitat. In fact, the recognition that the mountain pine beetle is a natural disturbance agent is central to Parks Canada's forest management strategy to use prescribed fire as its primary tool to manage beetle impacts. Because fire exclusion had resulted in a landscape with extensive stands of mature lodgepole pine suitable for beetle colonization, it therefore seemed ecologically appropriate to use fire to restore landscape heterogeneity, promote forest resilience in the long-term, and reduce fire risk. The 2003 Fairholme embodied this strategy and illustrated the maturity that the Banff fire program had achieved in 20 years—it is often given as an example to show that highly complex prescribed fires can be conducted in mixed-severity and stand-replacing fire regimes. The Fairholme not only reduced mountain pine beetle habitat but also combined prescribed fire and mechanical fuel management to improve wildlife habitat for wolves (*Canis lupus*), elk (*Cervus canadensis*), and grizzly bears (*Ursus arctos*), while creating a large (4,500 ha) fuel break upwind of the communities of Harvie Heights and Canmore. The Fairholme was a success despite extreme summer drought conditions in a season when many challenging fires burned in Canada's national parks and the western provinces. Lessons learned in 2003 led to many changes in prescribed fire planning, smoke management, mountain pine beetle management (Trzcinski and Reid 2008; Tabacaru et al. 2016), and resource allocation within Parks Canada. Similarly, a dozen national parks across Canada were now using fire to maintain ecological integrity.

Importantly, research on the role of fire in the Banff landscape continued to guide multiple objectives of the fire restoration program. Prescribed fires now contribute to the reintroduction of bison (*Bison bison*), a historic keystone species of the Banff landscape (Steenweg et al. 2016); the restoration of Douglas-fir and aspen grasslands; habitat management for a variety of wildlife including elk and species of conservation concern such as grizzly bear, olive sided flycatcher (*Contopus cooperi*), and caribou (*Rangifer tarandus*; Hamer and Herrero 1987; Sachro et al. 2005; Pengelly and Hamer 2006; Park 2016); and provide opportunities for restoring endangered plant species such as whitebark pine (*Pinus albicaulis*; Figure 4). These examples of ecocultural burning and land restoration illustrate the long-term commitment by Parks Canada to apply fire to the landscape for management purposes.

Since the initial re-introductions of fire in Banff, Parks Canada now routinely re-burns areas to reduce lodgepole pine seedling density, coarse woody debris, and tree cover while at the same time stimulating grass, aspen, and Douglas-fir regeneration. Recent research is providing new insight into interactions between fire frequency, severity, and vegetation succession showing that mixed-severity fire regimes contribute to vegetation diversity and differences in future fire probability and extent (Prichard et al. 2018). There is ongoing research exploring burn probability (as a function of ignition probability and fire behaviour) as well as assessing the effectiveness of landscape-level prescribed fire and fuel management practices across multiple national parks (Parisien et al. 2005).

In the future, climate change research suggests that Banff will experience conditions conducive to higher fire frequency and fire intensity (Wotton et al. 2017; Bergeron et al. 2004; Boulanger and Carr 2016). Possible increases in forest insect outbreaks and disease will also contribute to the complex interactions between fuel flammability, fuels, fire severity and extent (Price et al. 2013), and ecology. By emulating historic fire regimes and allowing frequent fire in the montane ecoregions, Banff fire managers aim to create more resilient and heterogeneous landscapes and reduce the potential extent and impact of future fires exacerbated by climate change. However, the sociopolitical context and risks within which managers must plan and implement fire restoration activities continues to increase in complexity, which may make the use of prescribed fire as a landscape management tool more challenging in the future.

It has been recognized that, because of a growing wildland-urban interface and increasing visitation to Banff, Park managers cannot solely rely on the use of fire for landscape restoration. It is now evident that prescribed fire must be coupled with strategic mechanical treatment of fuels that can serve as fuel breaks for naturally occurring fires, facilitate future implementation of prescribed fire, and provide ecological benefits themselves. Incorporating both the large-fire biophysical and ecocultural fire paradigms can be difficult when research and management priorities are often based on short-term perceived fire risk (White et al. 2011). If park managers focus on fire use and fuel treatment for a variety of ecological and cultural objectives, they may be able to mitigate risk from fires and climate change across the landscape and over the long-term.

6. Conclusions—future directions in wildland fire science

Clearly, Canadian wildland fire science has made great strides over the past 50 years due to the contributions of numerous individuals (Figure 5). Yet, many challenges remain for Canadian wildland fire science and operational fire management in the face of climate change and other anthropogenic impacts on forests. Fortunately, there has been a great deal of work focused on identifying pertinent future research priorities in the realm of wildland fire science and management (e.g., Coogan et al. 2019; Johnston et al. 2020; Tymstra et al. 2020). One significant moment in fire management came with the development of the Canadian Wildland Fire Strategy (CWFS; Canadian Wildland Fire Strategy Assistant Deputy Ministers Task Group 2005). The CWFS declaration provided a shared vision and set of principles for wildland fire management in Canada and was developed after comprehensive review by provincial, territorial, and federal governments. The CWFS was developed to support a new and innovative direction for wildland fire management in Canada and was focused on four strategic objectives including public education and awareness and policy and risk analysis, a national FireSmart initiative, preparedness and response capability, and innovation. Importantly, Sankey (2018) laid out future wildland fire research priorities and themes in the Blueprint for Wildland Fire Science in Canada (2019-2029) which builds upon the foundations of fire science that have been developed over the last 50 years (and longer) as per our review. These future priorities include: understanding fire in a changing world; recognizing Indigenous knowledge; building resilient communities and infrastructure; managing ecosystems; delivering innovative fire management solutions; and reducing the effects of wildland fire on Canadians (Sankey 2018).

As mentioned at the beginning of this paper, a fully comprehensive examination of the important developments related to all areas of wildland fire science is beyond the scope of this paper and the expertise of the authors. Such omissions are, in fact, a testament to the great range and depth of scientific advances made by numerous researchers in Canadian wildland fire science over the past 50 years. For one, there have been great strides in research on the human dimensions of wildland fire including issues related to fire management in the wildland-urban interface (Johnston and Flannigan 2018), evacuation responses (Beverly and Bothwell 2011; Asfaw et al. 2019), and homeowner risk mitigation and preparedness (McFarlane et al. 2011)—human dimensions research remains crucial for addressing wildland fire challenges now and into the future. Likewise, research relating to firefighter health and performance (Robertson et al. 2017), and the health and economic impacts of smoke (Rittmaster et al. 2006; Reisen et al. 2015), have made important contributions to wildland fire science over the past decades.

While the goal of using science-based models of the forest environment to provide situational intelligence to operational decision-makers has been a top priority, its importance continues to grow during the current era of risk management. There is an ongoing effort to develop the next generation of the Canadian FWI and FBP Systems to provide improved flexibility and a broader application in the challenging decision-making environment faced by modern fire managers. For instance, a more flexible fuel modelling structure is under development to address the modern need for fire behaviour prediction capacity in forests altered by insect outbreaks, storm damage, and fuel management treatments. Such a task requires a comprehensive redesign of many of the models; however, the benefits will be significant. These improvements to the FWI and FBP Systems will provide opportunities for new technological developments and data sources, now available as remotely sensed products such as Lidar and infrared or multispectral mapping from satellite, aircraft, or pilotless aerial platforms. In conjunction with improvements in weather prognosis and interpolation, these data will enhance the core Canadian fire information products of the CFFDRS for its users.

Fire and land management challenges have grown over the preceding decades and the need to more broadly inform decision-making is paramount. Therefore, researchers have continued to adopt new approaches and technological advances to overcome management challenges. The complexity of these problems highlights the opportunity to address future challenges using OR, machine learning, and artificial intelligence to enhance wildland fire science and management (e.g., Lagerquist et al. 2017). As computational power increases and large datasets become more available (including remotely sensed data), the use of machine learning has the potential to improve many aspects of fire science in novel ways including operational fire management, occurrence prediction, burn probability mapping, fuel treatment assessment, and forest and landscape planning (Jain et al. 2020). Furthermore, the continual advancement in remote sensing technologies have greatly helped scientists to monitor and better understand the dynamics of wildland fire. The WildFireSat satellite system, which is scheduled to launch in 2025, is currently being developed to enhance Canada's ability to manage wildland fires in the future (https://www.asc-csa.gc.ca/eng/satellites/wildfiresat/default.asp).

Recent large and intense fires have highlighted the long-term consequences of past fire exclusion and forest management practices that have led to the increased vulnerability of Canadian forests and communities (Parisien et al. 2020). Although there is general agreement that long-term solutions must include fire on the landscape, including modified-response fire and prescribed fire, specific strategies and methods to measure their efficacy are just now being developed in Canada. For example, pro-active management of hazardous fuels in the wildland-urban interface has been identified as a top priority in many jurisdictions; however, experimental frameworks and monitoring to ensure efficacy are needed. At landscape levels, diversifying forest management beyond conventional timber products will require interdisciplinary collaborations among fire scientists, forest ecologists, and managers. Much can be learned from successful fire management and restoration programs, such as in Banff, although restoration of landscape fire still faces many constraints and challenges in other protected areas and in multiple-use forests across Canada. Furthermore, increased opportunities for Indigenous involvement in fire management will enhance understanding of cultural fire use in Canada and foster better relationships between governmental land managers and Indigenous land stewards towards a common goal of ecosystem integrity and resilience. Wong et al. (2020) identified ten specific calls to action for natural scientists that can be applied to both wildland fire science and fire restoration to foster reconciliation with Indigenous Nations.

Importantly, climate change is anticipated to create additional wildland fire-related challenges to overcome in Canada, as we anticipate more active fire regimes and greater demands on fire management. One approach to adapt to this new reality would be to allow fire on the landscape when and where possible (Tymstra 2020). It is very likely that Canadians will have to learn to coexist in a future world with more wildland fire and associated smoke, which necessitates research to accommodate and manage for such a future. Of particular concern is the potential increase in high-intensity fires that are difficult to impossible to extinguish and threaten communities. With these and other challenges associated with the future of wildland fire, more resources will need to be invested in sustained research programs, such as the NSERC/Canada Wildfire Strategic Network, to train the next generation of scientists and continue the legacy of wildland fire science in Canada.

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TABLES

Table 1. Glossary of select fire science, ecology, and management terms used in this paper. Based primarily on the CIFFC (2017) Canadian Wildland Fire Management Glossary.

Burn Severity: see Fire Severity.

Canopy: That volume of a tree or forest stand consisting of branches and foliage, typically living.

Crown Fire: A fire that advances through the crown fuel layer, usually in conjunction with a surface fire.

Crown Fuels: The standing and supported forest combustibles not in direct contact with the ground that are generally only consumed in crown fires (e.g. foliage, twigs, branches, cones). See Surface Fuels, Ladder Fuels.

Crowning: A fire ascending into the crowns of trees and spreading from crown to crown.

Depth of Burn (DOB): The reduction in forest floor thickness due to consumption by fire, typically expressed in cm.

Fire Behaviour: The manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography.

Fire Cycle: The number of years required to burn over an area equal to the entire area of interest. See Fire Frequency, Fire Interval.

Fire Danger Rating: The process of systematically evaluating and integrating the individual and combined factors influencing fire danger represented in the form of fire danger indexes.

Fire Effects: Any ecosystem impacts attributable to a fire, whether immediate or long-term. May be detrimental, beneficial, or benign. See Fire Severity.

Fire Frequency: The average number of fires that occur per unit time at a given point. See Fire Cycle, Fire Interval.

Fire History: The study and/or compilation of evidence (e.g. historical documents, fire reports, fire scars, tree growth rings, charcoal deposits) that records the occurrence and effects of past wildfires for an area. See Fire Cycle, Fire Frequency.

Fire Interval: The average number of years between the occurrence of fires at a given point; also known as Fire Return Interval (FRI). See Fire Frequency, Fire Cycle.

Fire Management Planning: The systematic, technological, and administrative management process of determining the organization, facilities, resources, and procedures required to protect people, property, and forest areas from fire and to use fire to accomplish forest management and other land use objectives.

Fire Prevention: Activities directed at reducing fire occurrence; includes public education, law enforcement, personal contact, and reduction of fire hazards and risks.

Fire Regime: The kind of fire activity or pattern of fires that generally characterize a given area over a given time period. Some important elements of the characteristic pattern include fire cycle or fire interval, fire season, and the number, type, and intensity of fires.

Fire Season: The period(s) of the year during which fires are likely to start, spread, and result in negative impacts. The fire season is usually further divided on the basis of the seasonal flammability of fuel types (e.g. spring, summer, and fall).

Fire Severity: The ecological impact of fire on vegetation and soil, through organic matter consumption from flaming and smouldering combustion. See Fire Effects.

Fire Suppression: All activities concerned with controlling and extinguishing a fire following its detection.

Fire Weather: Collectively, those weather parameters that influence fire occurrence and subsequent fire behaviour (e.g. dry-bulb temperature, relative humidity, wind speed and direction, precipitation, atmospheric stability, winds aloft).

Fire Weather Index (FWI): A numerical rating of fire intensity that combines the Initial Spread Index and Buildup Index. It is suitable as a general index of fire danger throughout the forested areas of Canada.

Fuel Management: The planned manipulation and/or reduction of living or dead forest fuels for forest management and other land use objectives (e.g. hazard reduction, silvicultural purposes, wildlife habitat improvement) by prescribed fire, by mechanical, chemical, or biological means, and/or by changing stand structure and species composition.

Fuel Moisture Content: The amount of water present in fuel, generally expressed as a percentage of the fuel's dry weight when thoroughly dried at 100 ^{o}C.

Fuel Type: An identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behaviour under defined burning conditions.

Ladder Fuels: Fuels that provide vertical continuity between the surface fuels and crown fuels in a forest stand, thus contributing to the ease of torching and crowning (e.g. tall shrubs, small-sized trees, bark flakes, tree lichens).

Operational Fire Management: Fire management related to agency decision-making activities.

Prescribed Fire: The knowledgeable application of fire to a specific land area to accomplish predetermined forest management or other land use objectives.

Risk: The product of the likelihood of an event and its potential impact, which equals the expected or average impact. ('Risk' has many formal and informal definitions and uses (Johnston et al. 2020)).

Severity: See Fire Effects, Fire Severity.

Surface Fire: A fire that burns in the surface fuel layer (e.g. litter, herbaceous vegetation, low and medium shrubs, tree seedlings, stumps, downed dead roundwood), excluding the crowns of the trees.

Traditional Knowledge: The knowledge, innovations, and practices of Indigenous and local communities. Developed from experience gained over the centuries and adapted to the local culture and environment, traditional knowledge is transmitted orally from generation to generation.

Underburning: Prescribed burning under a forest canopy without the involvement of canopy fuels.

Wildland Fire Management: Fire management relating to ecological and fuel modification activities, such as prescribed fire and fuel treatments.

Wildland Urban Interface (WUI): The area where homes and other human development meets or are intermixed with wildland fire fuels.

CIFFC (Canadian Interagency Forest Fire Centre). 2017. Canadian Wildland Fire Management Glossary. Prepared by the CIFFC Glossary Task Team and Training Working Group, 16 October, 2017. Available at https://www.ciffc.ca/sites/default/files/2019-03/CIFFC_Canadian_Wildland_Fire_Mgmt_Glossary_2017_10_24.pdf [accessed 30 June 2020].

FIGURE CAPTIONS

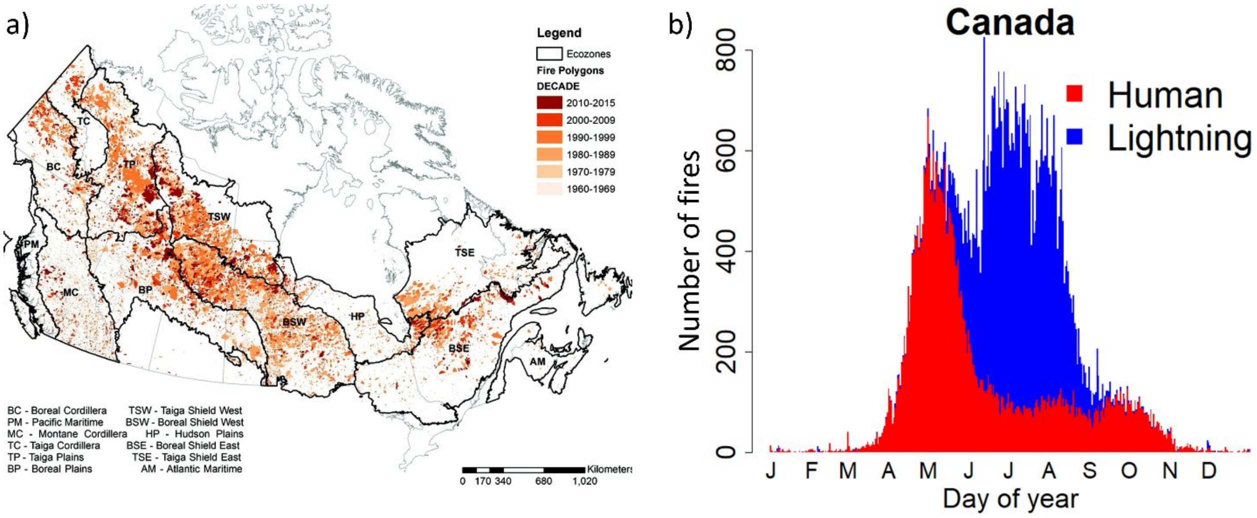


Fig. 1. (a) National distribution of large fire (>200 ha) polygons in Canadian ecozones. Figure adapted from Hanes et al. 2019. The base map was made in ArcGIS and includes the National Fire Database (NFDB) polygon data and Canadian ecozone polygons. (b) Stacked bar graph showing the number of new human- and lightning-caused fire occurrences (≥2 ha) for each day of the year from 1959-2018. Figure adapted from Coogan et al. 2020.

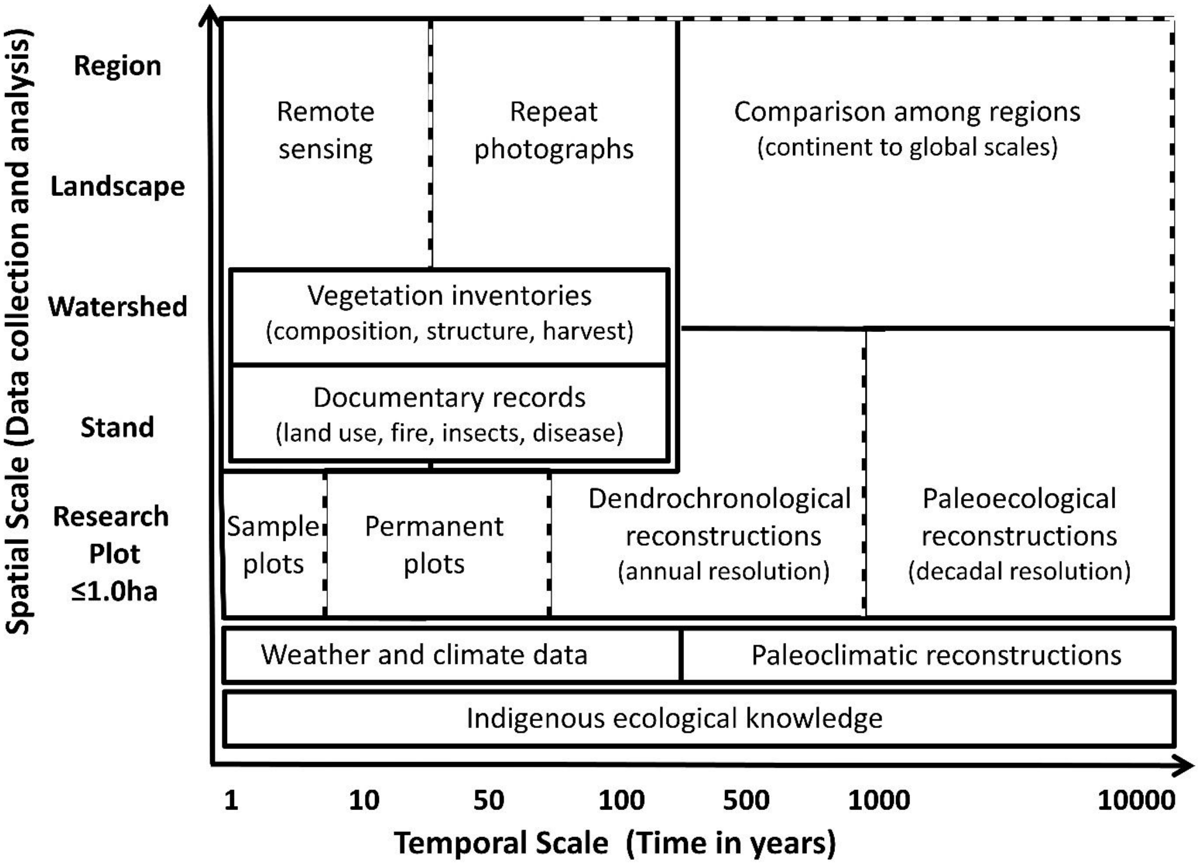


Fig. 2. Conceptual model of the spatiotemporal domains of research approaches used to characterize fire regimes.

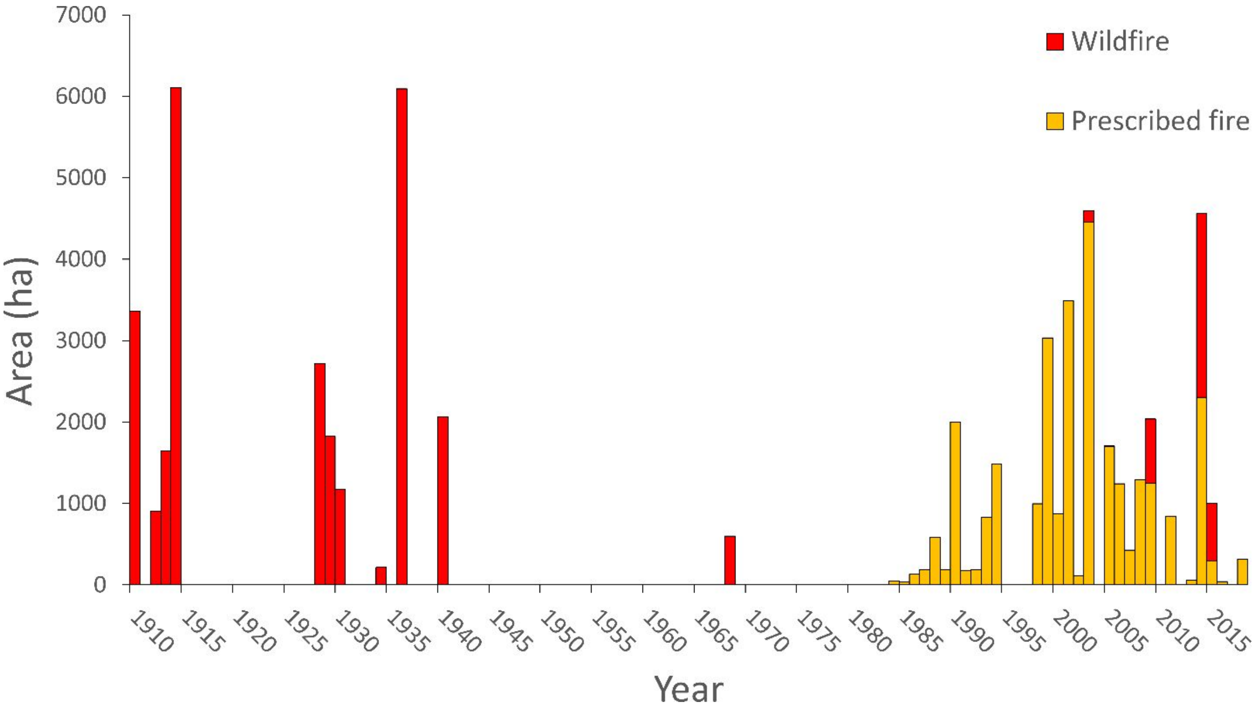
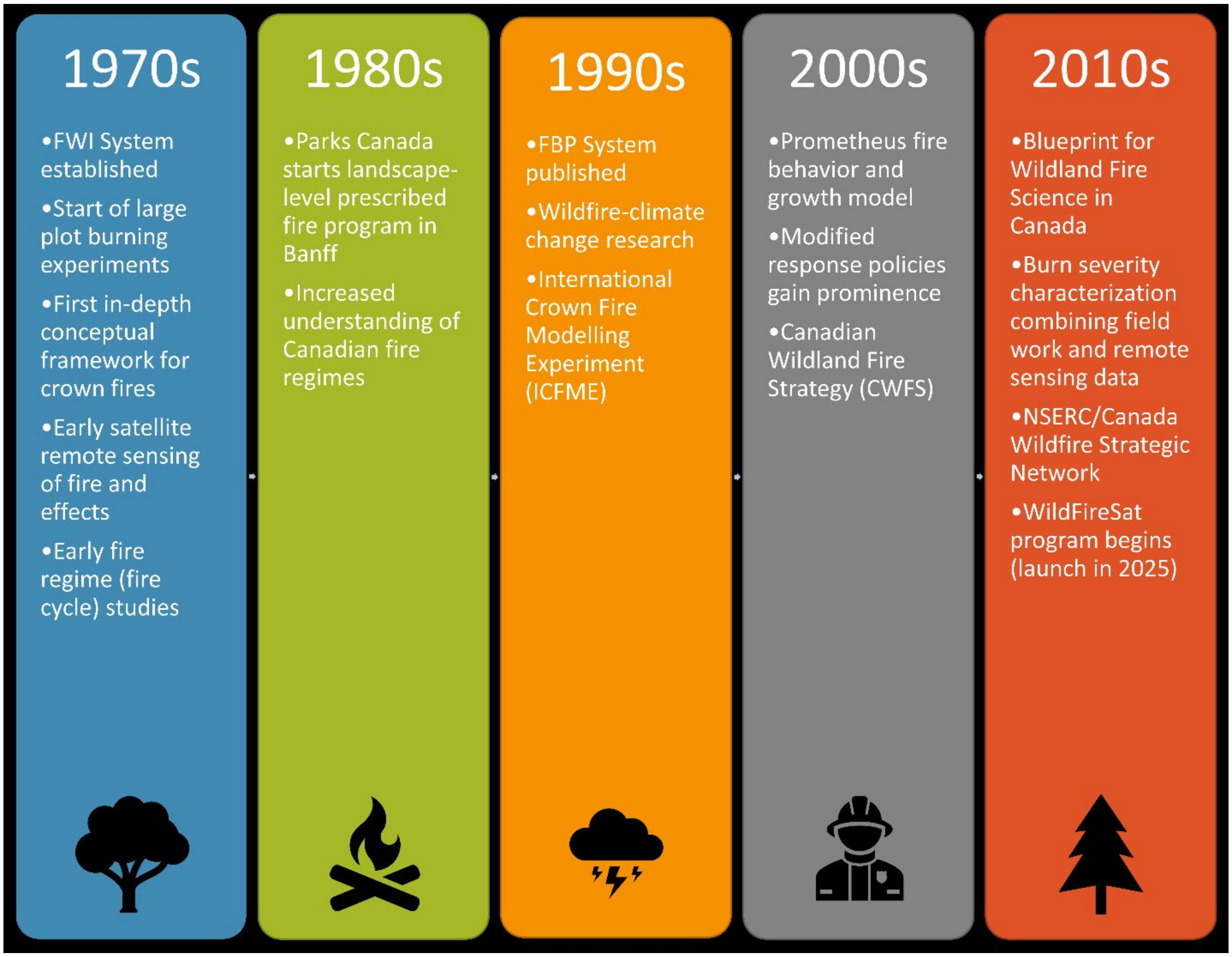


Fig. 3. Annual area burned (ha) by wildfire (red) and prescribed fire (amber) in Banff National Park from 1910 to 2018. Note the long period of fire exclusion from the 1940s until the early 1980s.

Fig. 4. The Sawback Prescribed Fire (October 2014). An example of a complex, landscape-level prescribed fire implemented by Parks Canada. These fires require significant public communication given their proximity to infrastructure (this fire was visible from the TransCanada highway), complex assessments of fuels, fire weather, and topography and require significant resources to implement. Photo credit: C. Siddall/Parks Canada.



1970s

- FWI System established
- Start of large plot burning experiments
- First in-depth conceptual framework for crown fires
- Early satellite remote sensing of fire and effects
- Early fire regime (fire cycle) studies

1980s

- Parks Canada starts landscape-level prescribed fire program in Banff
- Increased understanding of Canadian fire regimes

1990s

- FBP System published
- Wildfire-climate change research
- International Crown Fire Modelling Experiment (ICFME)

2000s

- Prometheus fire behavior and growth model
- Modified response policies gain prominence
- Canadian Wildland Fire Strategy (CWFS)

2010s

- Blueprint for Wildland Fire Science in Canada
- Burn severity characterization combining field work and remote sensing data
- NSERC/Canada Wildfire Strategic Network
- WildFireSat program begins (launch in 2025)

Fig. 5. Timeline of some key developments in Canadian wildland fire science by decade from the 1970s to the 2010s. Abbreviations: FWI = Fire Weather Index System; FBP = Fire Behaviour Prediction System.