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REVIEW

Wildland fire risk research in Canada

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Abstract: Despite increasing concern about wildland fire risk in Canada, there is little synthesis of knowledge that could contribute to the development of a comprehensive risk framework for a wide range of values, which is an essential need for the country. With dramatic variability in costs and losses from this natural hazard, there must be more support for complex decision-making under the uncertainty of how to assess and manage risk to coexist with wildland fire. A long history of Canadian wildland fire research offers solid foundational knowledge related to risk, but the key knowledge gaps must be addressed to fully consider risk in a comprehensive manner. We provide a review of the current context in which risk is variably defined, and recommend use of the general paradigm where risk is the product of both the likelihood and the potential impacts of wildland fire. We then synthesize research related to wildland fire risk from the Canadian scientific literature. With this review, we aim to provide a better understanding of research challenges, limitations, and opportunities for future work on fire risk within the country.

Key words: wildland fire risk, risk framework, fire occurrence, fire likelihood, fire impacts, risk management.

Résumé : Malgré les inquiétudes croissantes concernant les risques reliés aux feux de végétation au Canada, il existe peu de synthèses des connaissances qui pourraient contribuer à l'élaboration d'un cadre d'évaluation du risque considérant un large éventail d'enjeux. Pourtant, cette analyse représente un besoin essentiel pour le pays. Compte tenu de l'énorme variabilité des coûts et des pertes attribuables à ce danger naturel, il devrait y avoir davantage d'outils soutenant le processus de prise de décision complexe concernant la façon d'évaluer et de gérer le risque de coexister avec les feux de végétation dans un contexte d'incertitude. Au Canada, une longue expérience de recherche sur les feux de végétation offre de solides connaissances fondamentales sur les risques. Toutefois, les principales lacunes en matière de connaissances doivent être comblées afin de tenir pleinement compte des risques de façon exhaustive. Nous examinons le contexte actuel dans lequel le risque est défini de façon variable, et nous recommandons l'usage du paradigme général selon lequel le risque est le produit de la probabilité et des impacts potentiels des feux de végétation. Nous faisons ensuite une synthèse de la recherche sur les risques de feux de végétation dans la littérature scientifique canadienne. Grâce à cet examen, nous visons à mieux comprendre les défis, les limites et les possibilités en matière de recherche pour les travaux futurs portant sur les risques de feux au pays.

Mots-clés : risques de feux de végétation, cadre d'évaluation du risque, occurrence des feux, probabilité d'incendie, impacts du feu, gestion des risques.

1. Introduction

Fire and humans have shared the flammable landscapes of Canada for thousands of years, with Indigenous fire knowledge enabling the application of fire as a beneficial tool (Pyne 2007; Christianson 2015). In the 1920s, scientific research focusing on wildland fires began in Canada, and formal research agencies formed in 1960 (Pyne 2007). Early research largely focused on protecting both the public and the valuable timber resources in Canada, with fire being viewed as a threatening natural hazard (McCaffrey 2004). One of the major achievements of this early fire research was the creation of the Canadian Forest Fire Danger Rating System (CFFDRS), and its two main subsystems: the Fire Weather Index (FWI) System (Van Wagner 1987; Wotton 2009) and the Fire Behavior Prediction (FBP) System (Stocks et al. 1989; Forestry Canada Fire Danger Group 1992; Hirsch 1996; Wotton

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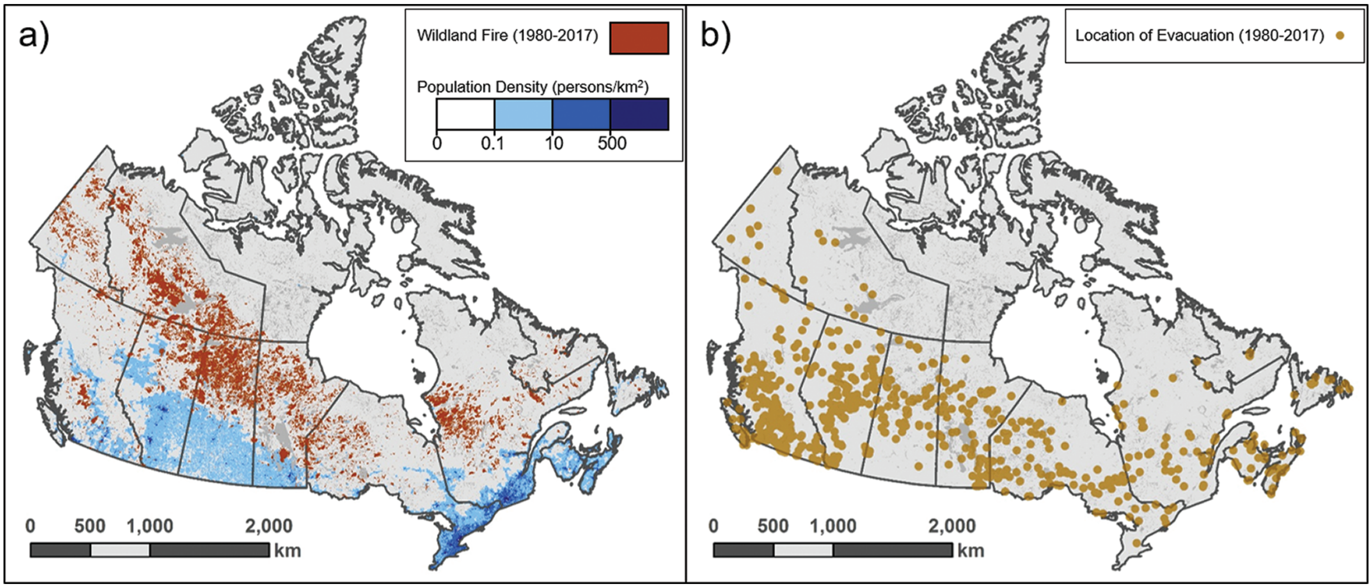
Fig. 1. Map of Canada overlaid with (*a*) recent (1980–2017) recorded fire activity (from the National Fire Database; Canadian Forest Service 2018*a*) and human population density (from the Gridded Population of the World; SEDAC 2018) and (*b*) locations of reported evacuations (1980–2017) (Canadian Forest Service 2019*a*).



et al. 2009). These products are used in day-to-day operational fire management activities and form the core working knowledge on wildland fire in Canada, yet the CFFDRS does not explicitly model fire risk.

In Canada, there is considerable interest in quantifying fire risk within the fire research community, but there is also interest in addressing this widespread natural hazard amongst fire management agencies, homeowners, municipalities, Indigenous communities, the forest industry, oil and gas operators, and the insurance industry. Significant fire activity occurs across much of the country (Fig. 1*a*; Erni et al. in press), with an average year resulting in millions of hectares of burned area (Coops et al. 2018; Hanes et al. 2019) and thousands of people evacuated (Fig. 1*b*; Beverly and Bothwell 2011). Indirect costs of wildland fires are very large yet difficult to quantify, but direct insurable losses indicate that wildland fire in Canada is one of the more costly natural hazards (Fig. 2). These losses are being experienced even with large investments designed to mitigate them (up to $1 billion a year is spent on fire management; Hope et al. 2016; Stocks and Martell 2016).

Despite the importance of wildland fire in Canada, fire risk research is still in its infancy in this country. Other natural hazards such as flooding and earthquakes have risk-assessment tools in use in Canada, yet there is no system for wildland fire (Lyle and Hund 2017). Reviews of fire risk (e.g., Blanchi et al. 2002; Thompson and Calkin 2011; Hyde et al. 2013; Miller and Ager 2013) and risk-assessment tools or formal frameworks (e.g., Bonazountas et al. 2005; Tolhurst et al. 2008; Chuvieco et al. 2010; Thompson et al. 2011; Maillé and Espinasse 2012; Scott et al. 2013; Leonard et al. 2014; Alcasena et al. 2017) have been developed in countries outside of Canada, considering the context of fire risk for where they were created. As pointed out by Thompson et al. (2016*a*), even within a country there is no universal solution and assessment of risk must be aligned with "…the context, purpose, and needs of decisionmakers". Due to Canada's unique vegetation, fire regimes, biophysical environments, and fire management across such a large and variable country, fire risk concepts must be revisited to address these perspectives.

Many challenges are faced when studying the impacts of fire and the likelihood of those impacts to assess wildland fire risk. In fact, fire risk has been referred to as a "socioecological pathology" (Fischer et al. 2016) and a "wicked problem" (Chapin et al. 2008) owing to its intricate nature. A truly comprehensive consideration of risk is an almost impossibly complex task, and furthermore, the dynamic aspects of risk also must be considered. For example, risk can change over time, with some changes being temporary and others being permanent. Wildland fire itself is also a complex and dynamic process and is controlled by weather and climate, fuels (i.e., flammable vegetation), ignitions, and human activities at multiple temporal and spatial scales (Flannigan et al. 2005; Hardy 2005; Scott 2006; Parisien et al. 2014; Coughlan et al. 2018; Tedim et al. 2018). Another challenge to assessing risk is that it involves considerable uncertainty (White 1995; Thompson and Calkin 2011; Scott et al. 2013; Miller and Aplet 2016), which perhaps is not only a challenge when studying risk, but also the essence of risk itself. Uncertainty can derive from the unknown and variable nature of wildland fire and from the unknowns surrounding fire impacts. Uncertainty can also be related to the human dimensions of fire, which may involve our complex influences on fire ignition and spread, subjective perceptions of risk and impacts, and even what we consider to be of value. In addition to these challenges, a lack of consistent wildland fire risk terminology is also a major barrier to effectively studying and communicating risk, which has been widely acknowledged in the literature (Bachmann and Allgöwer 2001; Finney 2005; Hardy 2005; Miller and Ager 2013; Thompson et al. 2016*a*).

Despite the challenges inherent to the investigation of wildland fire risk, there are many opportunities for an improved understanding of fire risk in a Canadian context. The objective of this paper is to provide a synthesis of knowledge on wildland fire risk in Canada, with the aim of informing and encouraging future work in answering the question "what is our risk from wildland fire?". We first examine the common terminology in the literature and propose a definition system for fire risk research in Canada. Second, we present a summary of the recent work pertaining to fire risk in Canada. Third, we discuss options for future directions of fire risk research and offer suggestions for how to best support risk management.

2. Defining wildland fire risk

Historically, wildland fire risk was simply defined as fire occurrence; it was determined by the number of fires, with no reference to the potential impacts of those fires (Simard 1977; FAO 1986;

Fig. 2. Insured losses (in billions, in 2018 dollars, as loss plus loss adjustment expenses) for catastrophic natural hazards in Canada by year from 1983–2016 (Insurance Bureau of Canada 2019). Categories of natural hazards include storm (wind, tornado, hail, lightning, rain), flooding, wildland fire, winter storm (ice or snow), and hurricane.

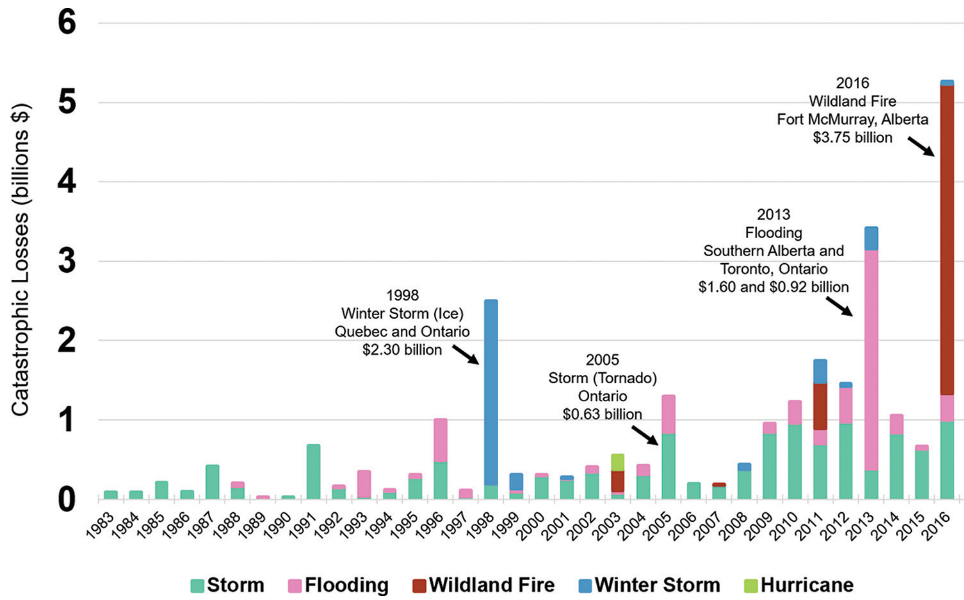
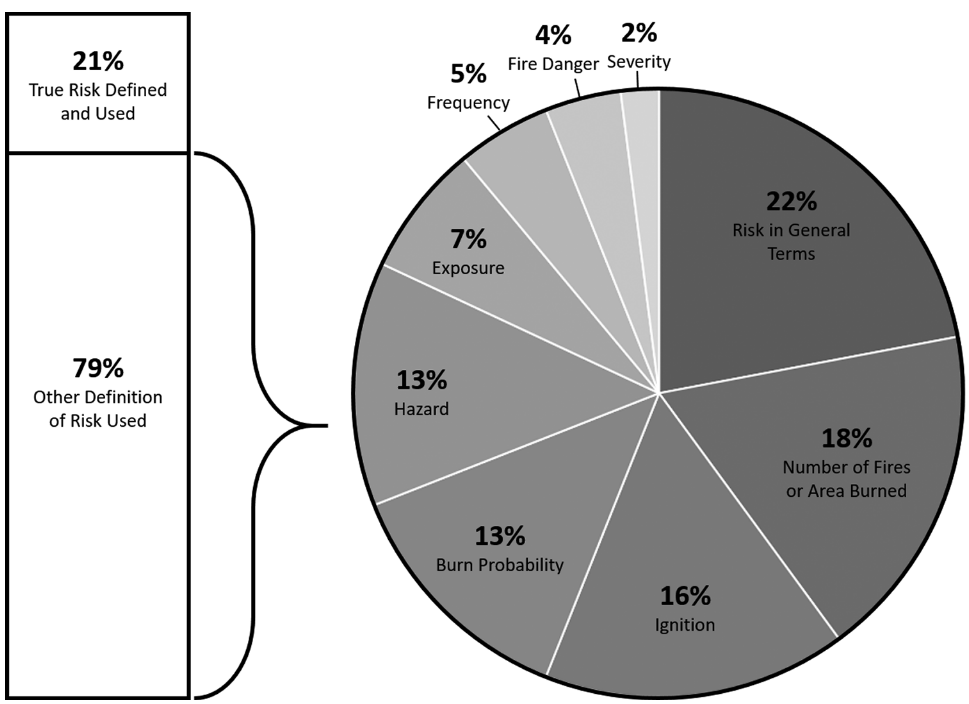


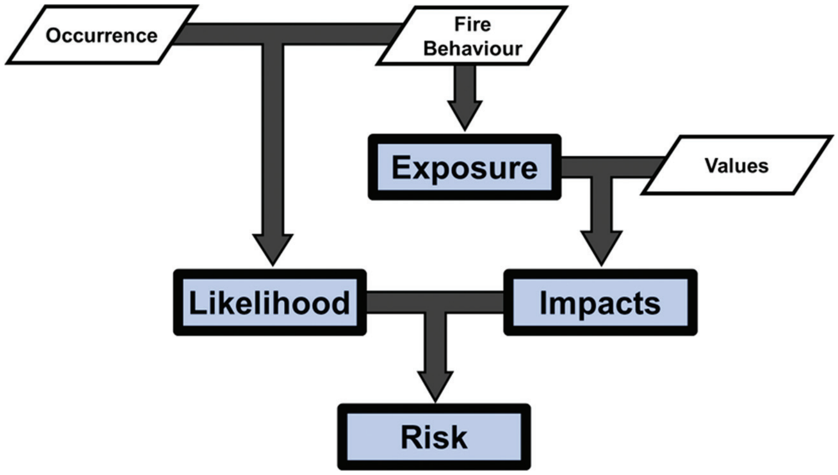
Fig. 3. Analysis of fire risk definitions used in wildland fire research literature. To compile this data, we analysed global references to risk in 175 conference papers, journal articles, and agency reports with search terms "wildfire" (or "forest fire", "wildland fire", or "bushfire") and "risk" using Google Scholar, Web of Science, and Science Direct; search was performed in November 2018. This was not an exhaustive or systematic review, but a sampling of what definitions could be encountered in the literature. Only 21% of papers used the technical natural hazards definition of risk, and 79% of papers were focused on one or more other parameters representing risk, or referred to risk in general terms with no definition or quantification.



Merrill and Alexander 1987; Hardy 2005). In contrast, the traditional risk definition used in natural hazards research sets risk as the expectation of loss or benefit and includes both probability of occurrence and potential impacts of the natural hazard (i.e., risk = likelihood × impacts; ISO 2009; UNISDR 2017). Within Canadian fire management agencies, this definition is partly applied when discussing "values at risk", which refers to values with a high probability of being affected (Calkin et al. 2011). In recent years, this natural hazards actuarial definition of risk has become conventional within quantitative fire risk frameworks (e.g., Finney 2005; Hardy 2005; Miller and Ager 2013; Scott et al. 2013; Chuvieco et al. 2014).

Despite the latter definition of risk becoming more common within wildland fire research, a multitude of definitions of fire risk

Fig. 4. Wildland fire risk and the primary components of wildland fire risk (rectangles), along with categories of inputs (parallelograms); definitions for the primary components can be found in Table 1.



persist in the literature. To illustrate this, we examined the existing literature on risk in wildland fire research, and we found that only 21% of papers used the technical natural hazards definition of risk (Fig. 3). Often, a measurable parameter such as burn probability or fire danger are used to represent risk, but there is little standardization, resulting in a frustrating variety of parameters used when referencing wildland fire risk (Fig. 3, Table A1). Reference to fire risk can also consist of a very general statement with no clear definition. For example, many articles discuss "being at risk from wildland fire" without further explanation, which has little functional meaning when used in this general way.

In this paper, we adopted the technical "natural hazards" definition of risk, thus considering the likelihood of fire and the potential impacts of fire. Accounting for both components of this risk equation is essential to properly assess trade-offs and effectively manage risk. To calculate the risk caused by an active fire involves identification of the possible outcomes based on fire behaviour that may produce those outcomes (i.e., conditional probability; Finney 2005). When calculating fire risk in general, we must also include the chance of ignition and the directional fire spread of the ignited fires (where fire spread is dependent on fire behaviour) and determine risk based on the possible range of fire behaviour that may be experienced. For example, a house may be subject to varying levels of risk under different fire conditions: a low-intensity and easily suppressed fire may not damage the structure, but a high-intensity crown fire may result in complete destruction. Furthermore, there can be positive benefits to the house (e.g., reduction of future fire risk) that must be weighed against the negative losses. To calculate the overall risk to an individual house, we must sum all levels of risk based on the range of fire behaviours that may be experienced. This can be expressed as:

$$\text{(1)}\qquad \text{Risk}_{\text{house}} = \sum_{i}^{N} p(F_i)[B_i - L_i]$$

where risk is represented as the sum of the probability of fire at the ith fire behaviour ($p(F_i)$) multiplied by the difference between potential benefits (B) and losses (L) over the potentially infinite range of N fire behaviours. Including both the benefits and losses reflects the change in the "all fire is bad" mentality and is crucial to determining the full impacts of a fire (Hardy 2005; Miller and Ager 2013).

Equation 1 can be expanded to determine risk on a variety of values such as humans (e.g., loss of life, lost wages, or mental health effects), infrastructure, ecosystem, habitat, or watersheds. Wildland fire risk can then be calculated as:

$$\text{(2)}\qquad \text{Risk} = \sum_{i}^{N} \sum_{j}^{n} p(F_i)[B_{ij} - L_{ij}]$$

where we modify eq. 1 by adding the impact on the jth value under consideration, summed over n values being considered. This equation is derived from the original version in Bachmann and Allgöwer (2000) and its revisions in Finney (2005) and Calkin et al. (2010). Based on eq. 2, we have produced a flow chart (Fig. 4) with the key elements constituting fire risk (Table 1).

Table 1. Definition of wildland fire risk and primary risk components used in this paper.

Term	Definition
Likelihood	Probability of wildland fire occurrence and wildland fire spread (based on fire behaviour), resulting in potential impacts of that fire (Finney 2005).
Impacts	Valuation of the effect of exposure experienced by a value, resulting in change according to the vulnerability of the value; impacts ultimately may be neutral, positive, or negative (McFayden et al. 2019).
Exposure	Incoming "thermal insult" (Caton et al. 2017) experienced by a value based on its location, irrespective of its resistance to the potential impacts of that exposure (Beverly et al. 2010; Maranghides and Mell 2012; Miller and Ager 2013).
Risk	Product of potential impacts from wildland fire and the likelihood of those impacts occurring (Bachmann and Allgöwer 2000; Finney 2005; Calkin et al. 2010).

2.1. Primary components of wildland fire risk

2.1.1. Likelihood

Likelihood is the probability of wildland fire happening (ISO 2009), potentially leading to impacts on a value; it can be computed using $p(F_i)$ from eq. 2. This calculation requires knowledge of two primary inputs (Fig. 4). The first is the expected fire behaviour (i.e., the *i*th fire behaviour), and the second is the probability of fire, which considers the potential for fire at a particular location, i.e., ignition and the fire spread at the given *i*th fire behaviour. When considering likelihood, the time period and spatial extent being considered must also be included. Likelihood is alternately referred to as fire hazard (as in Scott et al. 2013), which is avoided here as it has a variety of accepted definitions (Table A1).

2.1.2. Impacts

The consequences of fire are addressed by assessing impacts and are quantified by the difference between B_{ij} and L_{ij} from eq. 2. Impacts are calculated based on the given fire behaviour (in the case of a current fire) or over the range of possible fire behaviours (*i*), but there are a variety of approaches for simplifying and summarizing impacts (Finney 2005; Scott 2006). To calculate impacts, we require information on: (a) the values we are considering and their susceptibility, (b) the exposure of those values to fire behaviour that may result in impacts on those values (see section 2.1.3), and (c) some valuation of the change experienced to determine the impacts. The values included in a risk assessment are often called values at risk, but can alternately be referred to as highly valued resources and assets (Thompson et al. 2016*a*) or simply resources and assets (McFayden et al. 2019). Values may include life of residents or first responders, property, infrastructure, forest resources, culture, economy, fire management resources, ecosystem services, and environment (Simard 1977; Calkin et al. 2010; Tutsch et al. 2010; Eiser et al. 2012; Scott et al. 2013; Christianson 2015; Robinne et al. 2018; Sherry et al. 2019). Values may be impacted differently depending on how susceptible they are, i.e., their vulnerability (Scott 2006; Eiser et al. 2012; Scott et al. 2013; Beaver 2015; Xi et al. 2019). Vulnerability is not only based on the specific location of values but also their sensitivity and resilience (Turner et al. 2003; Eiser et al. 2012; Miller and Ager 2013) and is an essential component of determining impacts (Beaver 2015; Xi et al. 2019). The degree of susceptibility (i.e., vulnerability) is used here to refer to how the initial state of a value and its susceptibility govern the change experienced by a value (Turner et al. 2003; Scott 2006; Bhamra et al. 2011; Scott et al. 2013). However, susceptibility and vulnerability have a variety of meanings in the literature, including "fire susceptibility" (i.e., burn probability; Whitman et al. 2013), "social vulnerability" or "place vulnerability" (focusing on the socioeconomic factors that determine the ability of humans to resist or recover from impacts; Cutter et al. 2003; Ferrier and Haque 2003; Wigtil et al. 2016), and vulnerability in the insurance industry context where vulnerability is the degree to which an insured property may be affected (Crichton 1999).

Impacts and effects are often considered together as one component in risk assessments as an "effects analysis" (Miller and Ager 2013; Scott et al. 2013), but they can also be considered two distinct terms with effects "uncoupled" from the valuation of those effects (Thompson and Calkin 2011). Therefore, an effect represents the changes that a value experiences (i.e., first- or second-order fire effects; Reinhardt et al. 2001), such as a stand of trees being damaged or killed. Impacts include a human-defined assessment and valuation of the significance of that effect (McFayden et al. 2019); impacts on a stand of trees may include the economic loss of timber, loss of aesthetic appeal for recreational activities, and ecological benefits from improved forest health and habitat heterogeneity (Gould et al. 2013). The outcome of the effects (i.e., the impact) may result in a positive or negative impact, but the effect itself is a description of the actual change with no reference to the implications (Fig. 5; Hanewinkel et al. 2011; McFayden et al. 2019).

When determining impacts, valuation is subject to varying interests, worldviews, cultural values, experiences, and perceptions (Ferrier and Haque 2003; Finney 2005; McFarlane et al. 2011; Thompson and Calkin 2011; Eiser et al. 2012; Christianson 2015; Sherry et al. 2019). Additional decisions must be made about the relative importance or ranking of values (Scott et al. 2013). Furthermore, dynamic aspects of impacts should be considered and explicitly acknowledged in reference to the spatial and temporal scale of the overall assessment of risk (Simard 1991; Finney 2005; Hardy 2005; Thompson et al. 2016*a*). For example, a fire may have an immediate economic impact because of fire suppression costs, yet the longer-term impacts such as profit and job losses when small businesses are not capable of reopening after fire, psychological trauma experienced by people affected by the fire, or the implications of long-distance smoke effects on health and tourism may ultimately be more significant in a comprehensive view of risk. Resiliency can also modify impacts. For example, a resilient ecosystem may have reduced risk because it can quickly recover or adapt to a new state post-fire (Holling 1973; Turner et al. 2003; Le Goff et al. 2005; Bhamra et al. 2011; Chuvieco et al. 2014; Gauthier et al. 2014; Keane et al. 2018). Similarly, human communities can recover by rebuilding structures or can improve their adaptive capacity and reduce vulnerability to negative impacts through, for example, effective fire management policies (Simard 1977; Bhamra et al. 2011; McFarlane et al. 2011; Schoennagel et al. 2017; Xi et al. 2019).

2.1.3. Exposure

A component of impacts, exposure is the spatial union between a value and the behaviour of a wildland fire and represents the extent to which the value may be subjected to fire (ISO 2009). This spatial relationship between the values (and their susceptibility to effects) and their level of exposure (based on the incoming fire behaviour) are what determine the potential impacts of a given fire (Maranghides and Mell 2012; Miller and Ager 2013; Evers et al. 2019; Fig. 6). Exposure does not include likelihood, though the probability of exposure can be estimated by a probabilistic fire exposure analysis (as in Haas et al. 2013; Miller and Ager 2013; Scott et al. 2013; Evers et al. 2019). Furthermore, the estimate of exposure is independent of the impacts and the susceptibility to impacts; e.g., if a structure is very susceptible to ignition, this changes the impacts resulting from the exposure but does not change the exposure (Turner et al. 2003; Bhamra et al. 2011; Haas et al. 2013; Miller and Ager 2013; Scott et al. 2013; Caton et al. 2017). This definition of exposure in the context of natural hazards management is contrary to how the term is used in the insurance industry, where exposure is uniquely defined as the dollar value of insured property potentially at risk (Crichton 1999).

Fire exposure can be represented by a variety of metrics depending on what will cause effects (and corresponding impacts) on the value in question (Miller and Ager 2013). For example, exposure of a home depends on the magnitude and duration of heat flux represented by fire intensity and the potential for spotting, with spotting responsible for the majority of the catastrophic impacts of wildland fires (Cohen 1995; Beverly et al. 2010; Mell et al. 2010; Scott et al. 2013; Westhaver 2016; Caton et al. 2017). When considering exposure for ecological impacts, the relevant fire behaviour may include fire severity or intensity (Keeley 2009; Finney et al. 2011; Hyde et al. 2013; Scott et al. 2013). Exposure from a human health perspective would include exposure to smoke over potentially long distances, based on smoke emissions, duration, concentration, and composition (Ohlson et al. 2006; Reisen et al. 2015; Munoz-Alpizar et al. 2017).

3. Fire risk research in Canada

Despite a long history of fire research in Canada, we do not have a formal risk framework or risk-assessment procedures as in the United States (Calkin et al. 2010; Finney et al. 2011; Thompson et al. 2011; Scott et al. 2013), parts of Europe (Caballero 2004; Bonazountas et al. 2005; Chuvieco et al. 2010; Maillé and Espinasse 2012; Alcasena et al. 2017), and Australia (Tolhurst et al. 2008; Leonard et al. 2014). In Canada, early work using cost–benefit

Fig. 5. Illustration showing examples of the diverse effects of wildland fire.

analysis techniques (Sparhawk 1925; Headley 1943) did, however, address issues related to fire risk pertaining to fire economics, fire management, and level of protection (Muraro 1968; Simard 1977; Fuglem et al. 1983). Additionally, there is work on quantitative methods to assess costs and benefits within forest management and timber supply (Muraro 1968; Fuglem et al. 1983; Boychuk and Martell 1996; Thompson et al. 2000; Armstrong 2004; Savage et al. 2010). Some fire management agencies in Canada currently incorporate some form of risk assessment in their decision-making using internal agency systems (e.g., Ohlson et al. 2003; Ontario Ministry of Natural Resources 2013; BC Wildfire Service 2017; Saskatchewan Wildfire Management Branch 2019). Insurance companies in Canada use flood, earthquake, and hurricane risk assessments, but fire risk assessments are still lagging despite significant insurance payouts due to wildland fires (e.g., \$3.7 billion of direct insurable losses from the fire that damaged Fort McMurray, Alberta, in 2016; MNP 2017).

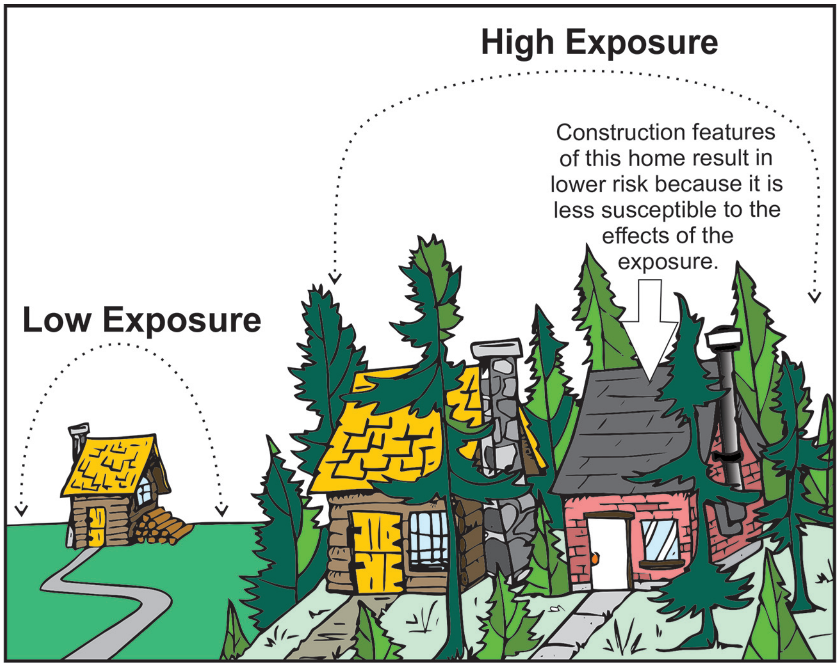
We have much of the information, tools, and models required to make a concerted effort to look closer at risk. Fire risk is a multi-faceted concept that integrates many different disciplines of fire research (as discussed in Bachmann and Allgöwer 2001), many of which are well established in Canada. We present an overview of Canadian research related to the two major components of risk: likelihood and impacts.

3.1. Likelihood research

To address the likelihood component of risk, extensive knowledge of fire occurrence (section 3.1.1) and behaviour (section 3.1.2) is required (Fig. 4). Globally and within Canada, there is a large body of research on fire activity controls using a variety of methods (e.g., Krawchuk and Moritz 2014; Williams and Abatzoglou 2016; Abatzoglou et al. 2018; Xi et al. 2019). Fire activity across the landscape is the result of fire ignition and spread of individual fires, and it is primarily controlled by fuels, climate (and its short-term manifestation, weather), ignition agents, and humans (Flannigan et al. 2005).

The presence of fuel to burn and the characteristics of that fuel (including continuity, volume, structure, and moisture content) strongly influence fire behaviour and the overall fire activity (Forestry Canada Fire Danger Group 1992; Cumming 2001). Many studies have investigated the role of fuel continuity (Kafka et al. 2001; Drever et al. 2008; Gralewicz et al. 2012*a*; Parisien et al. 2014; Cavard et al. 2015; Lehsten et al. 2016; Nielsen et al. 2016; Portier et al. 2016), stand age (Kafka et al. 2001; Krawchuk and Cumming 2011; Terrier et al. 2013; Héon et al. 2014; Bernier et al. 2016; Erni et al. 2018; Stralberg et al. 2018), and fuel composition such as deciduous–coniferous proportions on fire activity (Cumming 2001; Hély et al. 2001; Krawchuk et al. 2006; Drever et al. 2008; Gralewicz et al. 2012*a*; Girardin et al. 2013*a*; Terrier et al. 2013; Cavard et al. 2015; Bernier et al. 2016). In addition to the physical

Fig. 6. Illustration of structures with varying wildland fire exposures and sensitivity/resistance to that exposure. The houses directly adjacent to fire in continuous forested fuels have higher exposure compared to homes separated by a large distance from fuels. The houses with fire-resistant construction features (e.g., fire-resistant roof, windows, siding) experiences the same exposure as the neighboring house, but is less susceptible to negative impacts.



characteristics of fuels, fuel moisture notably plays a strong role in governing fire occurrence (Martell et al. 1987, 1989; Wotton and Martell 2005; Woolford et al. 2014), and also fire intensity and spread (Johnson and Wowchuk 1993; Flannigan et al. 2005; Wotton et al. 2010; Thompson et al. 2019).

Climate and the resultant shorter-term weather are important factors relevant to fire activity (Carcaillet et al. 2001; Flannigan et al. 2005). Temperature, wind speed, precipitation, and relative humidity form the primary inputs into the FWI System. Van Wagner (1987) provided an overview of the FWI System and summarized a variety of studies investigating how well the FWI codes relate to the fire activity. Many studies found that various components of the FWI System have a strong predictive ability for fire activity in Canada (Vega-Garcia et al. 1995; Lefort et al. 2003; Girardin et al. 2004; Flannigan et al. 2005; Wotton and Martell 2005; Girardin and Wotton 2009; Le Goff et al. 2009; Parisien et al. 2011*a*; Cavard et al. 2015) and for area burned in many parts of the world (Abatzoglou et al. 2018). Additionally, combinations of FWI System components along with weather variables (Flannigan et al. 2005; Le Goff et al. 2009; Parisien et al. 2011*a*; Magnussen and Taylor 2012) or various combinations of weather variables (Drever et al. 2009; Whitman et al. 2015) were often effective at predicting fire activity. Of the weather variables, temperature (represented as means, maximums, or minimums over a season or year) often performs best among climate variables, or is at least included in the models (e.g., Pew and Larsen 2001; Gillett et al. 2004; Drever et al. 2009; Krawchuk et al. 2009*b*; Aldersley et al. 2011; Parisien et al. 2011*a*, 2014; Woolford et al. 2014; Whitman et al. 2015; Kitzberger et al. 2017). This is unsurprising because of the pervasive influence of temperature on fire activity through fuel drying, atmospheric moisture, and lightning activity (Wotton et al. 2010). Precipitation, or the interplay between temperature and precipitation, has often been shown to be important climatic variables for both global (Krawchuk et al. 2009*b*; Aldersley et al. 2011; Abatzoglou et al. 2018) and Canadian fire activity (Drever et al. 2008; Meyn et al. 2013; Whitman et al. 2015). Drought or precipitation frequency is more important than precipitation totals for controlling fire activity, particularly when studied with respect to high-pressure, upper-level blocking ridge patterns (Flannigan and Harrington 1988; Johnson and Wowchuk 1993; Flannigan and Wotton 2001; Xiao and Zhuang 2007; Drever et al. 2009; Héon et al. 2014; Portier et al. 2016). At much larger spatial and temporal scales, ocean temperatures and long-distance teleconnection patterns such as El Niño-Southern Oscillation are associated with fire activity (Johnson and Wowchuk 1993; Skinner et al. 2006; Le Goff et al. 2007; Xiao and Zhuang 2007; Meyn et al. 2010; Wang et al. 2010; Campos-Ruiz et al. 2018). Weather also controls fire activity through its impacts on fuel availability (through fuel moisture), fire ignitions (through lightning occurrence and fuel receptivity to ignition), and fire spread (through fuel moisture and wind) (Van Wagner 1987; Cruz et al. 2003; Flannigan et al. 2005; Wotton and Martell 2005; Peterson et al. 2010).

Topography can have an indirect effect on ignition patterns, fire spread, and fire weather through its effects on local climate and fuels (Forestry Canada Fire Danger Group 1992; Hély et al. 2001; Peterson et al. 2010). The Canadian FBP System accounts for slope and aspect, with steeper, south-facing slopes generally experiencing more extreme fire behaviour (Stocks et al. 1989). Varying topographic effects at different spatial scales (Cyr et al. 2007; Parisien et al. 2011*a*) and strong interactions with vegetation and weather (Cavard et al. 2015) can affect the bottom-up controls on fire activity, which may explain why topography is a weak predictor of fire behaviour or activity at some spatial scales (Kafka et al. 2001; Cary et al. 2006).

Humans cause about half of all wildland fire ignitions in Canada (Coughlan et al. 2018), but lightning-caused fires typically result in larger fires and thus are responsible for the majority of the area burned in the country (Stocks et al. 2002; Hanes et al. 2019). As an ignition agent, human activity directly affects wildland fire likelihood, but humans also exert direct effects from fire suppression, as well as a variety of indirect controls on fire activity, such as fire detection, mitigation, land use activities, and climate change (Pyne 2007; Flannigan et al. 2009; Krawchuk et al. 2009*a*; Bowman et al. 2011; Gralewicz et al. 2012*a*; Coughlan et al. 2018; Cardil et al.

2019). The net effect of human activities is highly complex, as they can either promote or restrain fire and are often difficult to measure. As stated by Parisien et al. (2016, p. 11), "Because of this complexity, the specific mechanisms by which humans alter fire ignition and spread may be difficult, or even impossible, to identify." Despite these difficulties, some progress has been made in Canada to show how various aspects of human influence control fire activity (at least in part). A generally negative relationship between humans and fire activity seems to prevail (Drever et al. 2008; Pechony and Shindell 2010; Aldersley et al. 2011; Robinne et al. 2016), but a variety of factors have been found to confound the relationship. These factors include fire regimes (Gralewicz et al. 2012*a*; Bistinas et al. 2013; Héon et al. 2014), suppression effectiveness (Martell and Sun 2008; Braun et al. 2010; Cardil et al. 2019), fire management policies (Gralewicz et al. 2012*b*), fuel treatments (Parisien et al. 2007), forestry operations (Muraro 1968; Hirsch et al. 2001; Pew and Larsen 2001; Palma et al. 2007; Acuna et al. 2010), scale effects (Parisien et al. 2011*a*, 2014; Gralewicz et al. 2012*b*), intensity of human impact (Bistinas et al. 2013; Knorr et al. 2014; Whitman et al. 2015; Parisien et al. 2016; Campos-Ruiz et al. 2018), and ignition limitation (Krawchuk et al. 2009*a*; Aldersley et al. 2011; Parisien et al. 2016).

3.1.1. Fire occurrence

The likelihood side of the risk equation requires an estimate of the probability of fire igniting or that a fire has already occurred. The Canadian Fire Occurrence Prediction (FOP) System is technically a component of the CFFDRS that focuses on the occurrence of human- and lightning-caused fires (Wotton 2009), but the probability of fire occurrence for daily or weekly decision-making is largely estimated by local fire management agencies. These occurrence predictions are typically based on daily fire weather, lightning activity, human activity, and local experience.

There are many existing occurrence prediction approaches (Wotton 2009; Xi et al. 2019). For research purposes, the spatiotemporal variability in ignition patterns and predictive occurrence models are commonly assessed through statistical procedures (Xi et al. 2019), e.g., Kernel, logistic, Poisson, or logistic generalised additive models (Vega-Garcia et al. 1995; Pew and Larsen 2001; Wotton et al. 2003, 2010; Krawchuk et al. 2006; Wang and Anderson 2011; Gralewicz et al. 2012*b*; Magnussen and Taylor 2012). Fire occurrence models typically include variables believed to influence ignition potential (fuels, fuel moisture, ignition source, weather) and, depending on the focus of the analysis, other explanatory variables such as historic spatial and seasonal trends, vegetation type, the number and attributes of lightning strikes, population, and road density (Taylor et al. 2013; Woolford et al. 2014, 2016; Xi et al. 2019). Algorithmic procedures (e.g., artificial neural networks, random forest) have also been used to predict fire occurrence as a function of other variables (Vega-Garcia et al. 1996; Syphard and Keeley 2015; Xi et al. 2019), but their applications still remain relatively limited in Canada. Comparisons between statistical and algorithmic procedures have revealed that both techniques show acceptable levels of predictive ability of fire ignitions, although algorithmic models present a better accuracy and robustness (Bar-Massada et al. 2013). Overall, human- and lightning-caused ignitions are usually considered separately (as seen in Wang and Anderson 2011), given that the underlying processes generating the ignitions are distinct and lead to unique spatial and temporal patterns (Flannigan and Wotton 1991; Krawchuk et al. 2006; Morissette and Gauthier 2008; Blouin et al. 2016; Coughlan et al. 2018).

3.1.2. Fire behaviour

Fire behaviour is a major contributor to the likelihood of fire (Fig. 4). The spread of a fire is driven by fuels, weather, and topography. In Canada, the primary fire research product related to wildland fire behaviour is the Canadian FBP System, which was developed using a largely empirical approach (Stocks et al. 1989; Forestry Canada Fire Danger Group 1992; Hirsch 1996; Wotton et al. 2009). Together with the FWI System, the FBP System has become deeply integrated into fire management systems and tools across Canada and other countries (Parisien et al. 2005; Taylor and Alexander 2006; Wotton et al. 2009; Tymstra et al. 2010; de Groot and Goldammer 2013). The outputs of the FBP System are also available as a national daily product on the Canadian Wildland Fire Information System (Canadian Forest Service 2019*b*). Tools including the widely used "Red Book" (Taylor et al. 1996), REDapp (REDapp Team 2018), and the cffdrs R package (Wang et al. 2017) have been developed for the calculation of these indices. Research on fire behaviour has been thoroughly reviewed by Sullivan (2009*a*, 2009*b*, 2009*c*), Wotton (2009), and Caton et al. (2017).

3.1.3. Estimating likelihood

Fire likelihood results from the combination of fire occurrence and fire spread according to the fire behaviour (Fig. 4) and therefore needs to account for fire propagation and direction from distant ignitions. Alternatively, ignition probability alone can be used to represent likelihood when calculating risk in some cases (Alcasena et al. 2015), but this measurement of likelihood is not equivalent to calculating burn probability (which incorporates both fire ignition and spread). Miller and Ager (2013, p. 3) articulated the distinction between these terms: "Typically, ignition probability is statistically modelled using fire occurrence data whereas burn probability is estimated via simulation. The two representations can exhibit vastly different spatial patterns…and tend to be used for different purposes. For example, estimates of ignition probability are used in initial attack simulations and burn probabilities are more often applied in fuels management planning problems."

With regard to fire spread, many methods exist to spatially model individual wildland fire growth (Sullivan 2009*a*, 2009*b*, 2009*c*), originally built either on empirical (i.e., statistical), theoretical (i.e., physical), or hybrid foundations (Pastor et al. 2003). Nevertheless, assessing fire likelihood for risk assessment requires a landscape-scale spatial approach to estimate the probability of burning with a given fire behaviour at each point within the area of interest (Finney 2005; Scott et al. 2013). To this end, spatial fire simulation models can be used to simulate the ignition and spread of thousands of fires under a wide range of environmental combinations. Many fire simulation models have been developed outside of Canada, including FSim (Parisien et al. 2019) and FlamMap (Finney 2006). Within Canada, Burn-P3 is a stochastic simulation model that produces burn probability maps (but also other outputs such as fire intensity, fuel consumption, and rate of spread; Parisien et al. 2005) and is based on the Prometheus fire growth model (Tymstra et al. 2010). The model combines deterministic fire growth on a static landscape (physiography, topography, and fuels) with probabilistic handling of fire ignition, duration, and weather. Likelihood is then given by the calculation of burn probability, i.e., the number of times each grid cell on a landscape burned divided by the total number of iterations of a simulation. Burn probability can be applied in a variety of applications (Parisien et al. 2019). For instance, it has been used in assessments of burn probability (Braun et al. 2010) and in determining the contribution of individual components to the spatial pattern of burn probability (Parisien et al. 2011*b*, 2013; Parks et al. 2012; Thompson et al. 2019). It has also been useful addressing various aspects of fire activity (Wang et al. 2016; Erni et al. 2018; Stralberg et al. 2018) and in probability-based municipal WUI delineation (Whitman et al. 2013). Fuel management strategies have also been tested using Burn-P3, through the effects on fire likelihood of prescribed fire treatments (Beverly et al. 2009), fuel break configuration (Parisien et al. 2007), or effectiveness of mitigation measures on habitat quality of caribou (Stockdale et al. 2019).

Table 2. Examples of data sources for inputs that may be required to quantify the wildland fire likelihood and impacts components of fire risk to people in Canada.

Risk component	Data	Possible data source(s)
Likelihood	Fuel	National Fire Behavior Prediction (FBP) fuel type maps (Nadeau et al. 2005; Simpson 2014; Taylor et al. 2019)
		Provincial/territorial fuel type maps (internal to fire management agencies)
		Land cover (e.g. Latifovic et al. 2004; Hermosilla et al. 2018)
		Remotely sensed products (e.g. Cihlar and Beaubien 1998; Power and Gillis 2006; Pouliot et al. 2014; Guindon et al. 2014, 2018; Olthof et al. 2015; Latifovic et al. 2017; Natural Resources Canada 2019*a*)
		National Forest Inventory (NFI) plot data (National Forest Inventory 2019)
		Satellite-derived products combined with NFI (Beaudoin et al. 2014)
		Community-level detailed fuels data (locally available)
		Plot-level plant traits (Bruelheide et al. 2018)
	Weather	National and provincial weather stations as raw data or inputs to the Fire Weather Index (FWI) System (Wotton 2009)
		Interpolated weather data (e.g. Flannigan and Wotton 1989; Beck et al. 2017; Hanes et al. 2017; Cai et al. 2018)
		Historical atmospheric and surface climatology from the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR; Mesinger et al. 2006; Jain et al. 2017)
		Global FireWeather Database (GFWED; Field et al. 2015)
	Topography	Digital elevation models (DEMs) (various available, e.g. Canadian Digital Elevation Model; Natural Resources Canada 2019*b*)
	Human activities	Population density (e.g. census data; Statistics Canada 2019)
		Structure locations from community-based data sets (locally available) or nationally available CanVec data set (Natural Resources Canada 2019*a*)
		Human-caused ignition models (various; see Wotton 2009)
		Proxies indicating human impact on likelihood, e.g. “human footprint”, roads, population, structures, and fire suppression (Drever et al. 2008; Acuna et al. 2010; Aldersley et al. 2011; Gralewicz et al. 2012*a*; Parisien et al. 2014; Hope et al. 2016; Johnston and Flannigan 2018)
	Fire	National Fire Database (NFDB; Stocks et al. 2002; Canadian Forest Service 2018*a*; Hanes et al. 2019)
		Remotely sensed data (Giglio et al. 2013; Lehsten et al. 2014; Allison et al. 2016; Coops et al. 2018; Johnston et al. 2018)
		National Burned Area Composite (NBAC) from combining NFDB with remotely sensed data (de Groot et al. 2007; Canadian Forest Service 2018*b*)
		Global products (wide variety available; Mouillot et al. 2014; Krawchuk and Moritz 2014; Chuvieco et al. 2016; Andela et al. 2019; Laurent et al. 2019; Chuvieco et al. 2019)
		Proxies for longer-term fire history, e.g. fire scars on trees (Héon et al. 2014), stand recruitment patterns (Bergeron et al. 2004; Portier et al. 2016; Erni et al. 2017), charcoal from sediment cores (Carcaillet et al. 2001; Power et al. 2008; Hély et al. 2010; Girardin et al. 2013*a*), and ammonium concentration in ice cores (Yalcin et al. 2006)
		Fire danger indices from the FWI system, available from the Canadian Forest Service (Canadian Forest Service 2019*b*) or the Global Early Warning System (Cantin 2019)
		Fire behaviour calculated from the FBP System (Stocks et al. 1989; Forestry Canada Fire Danger Group 1992; Hirsch 1996; Wotton et al. 2009)
Impacts	Human population	Census (Statistics Canada 2019)
		Night lights (Gralewicz et al. 2012*b*)
		Ecumene data sets (Weiss et al. 2008; Eddy et al. 2016; Natural Resources Canada 2016)
	Structures	Municipal parcel data (locally available)
		Classification of structure locations (e.g. CanVec; Natural Resources Canada 2019*a*) from high-resolution remotely sensed imagery
		Areas of wildland fuel surrounding structures and infrastructure combined with wildland fuel (i.e. “interface” areas; Johnston and Flannigan 2018)
	Socioeconomic	Census (Statistics Canada 2019)
		Community data (locally available)

Though valuable tools for fire risk assessment, fire simulation models are computationally demanding and data hungry. Their inputs require data from numerous sources (e.g., forest inventories, daily fire weather, historical fire perimeters, ignition grids) on a time period long enough to capture the variability of fire regimes and on a spatial scale fine enough to model the heterogeneity of environmental drivers of fire (Parisien et al. 2007; Bar-Massada et al. 2009; Ager et al. 2010; Miller and Ager 2013; Krawchuk and Moritz 2014). Though there is room for improvement with regards to data availability (see section 4.2.1), there are many useful sources of data when assessing wildland fire likelihood in Canada (Table 2). To reduce the intensive processing demands of simulations when faced with potentially infinite possible combinations of fire and weather, averages or extreme conditions are typically the focus (Finney 2005; Scott 2006; Bar-Massada et al. 2009). Modern developments in computing have reduced major technical limitations for estimating likelihood on a larger scale and with greater detail (e.g., Thompson et al. 2016*b*).

3.2. Impacts research

Impacts can be positive or negative, short- or long-term, direct or indirect, and are often framed by conflicting objectives and intricate sociological factors (Sherry et al. 2019). Risk can include the potential impacts on a wide range of values (Fig. 5; section 2.1.2) with many complex indirect factors to consider. Traditionally, most concerns with wildland fire risk pertain to the potential harm to humans and to structures (such as homes, businesses, and community buildings) and critical infrastructure (such as water supply and electrical networks) built by humans. The areas where these effects are a concern are where humans, communities, and infrastructure meet with or are interspersed within wildland fuel; this is referred to as the wildland–urban interface (WUI; USDA and USDI 2001). In Canada, a national map of WUI locations has been developed, which delineates what areas of wildland fuels would have the potential for effects on human-built structures in the event of a fire (Johnston and Flannigan 2018).

In Canada, homes and other community structures are frequently affected by fire. The most dramatic example is the catastrophic impacts seen in Fort McMurray, Alberta, in 2016 where over 2400 structures were destroyed (MNP 2017; Public Safety Canada 2018). Industrial structures and infrastructure (e.g., roads, power lines) can also incur very costly direct damages, with potentially even more dramatic and far-reaching indirect effects (MNP 2017; Johnston and Flannigan 2018; Council of Canadian Academies 2019). For example, damage to electrical or communications infrastructure can affect large urban areas far beyond the burn perimeter, and interruption of industrial production can cause significant economic losses.

Wildland fire activity and people do not overlap for large parts of the country (Fig. 1*a*; Bowman et al. 2017), which may partly explain why there has only been one direct civilian death from wildland fire since 1938 in Canada (Alexander 2010; Beverly and Bothwell 2011). When a fire does occur near communities, we depend on extremely effective initial attack and evacuations (Fig. 1*b*; Cumming 2005; Martell and Sun 2008; Beverly and Bothwell 2011; Johnston and Flannigan 2018; Sherry et al. 2019). However, the effectiveness of suppression to affect fire regimes and to prevent negative impacts on human populations has not reached consensus in the literature (Ward and Tithecott 1993; Johnson et al. 2001; Martell and Sun 2008; Braun et al. 2010; Parisien et al. 2016). In addition to fire suppression, fire management can also protect individual structures or areas of structures (i.e., values protection). Preventative actions can be taken to reduce the vulnerability of a structure or property to wildland fire. To that end, Canada has a FireSmart program that provides guidelines for homeowners and land managers (Partners in Protection 2003; Westhaver 2016). Building codes for making structures less vulnerable to wildland fire exist (International Code Council 2017; Manzello and Quarles 2017; NFPA 2019), but currently Canada only has codes for structural fires. Detailed measurements of radiant structure ignition were investigated as part of the International Crown Fire Experiment in the Northwest Territories (Cohen 2004; Stocks et al. 2004). However, a full structure ignition model (e.g., Manzello and Quarles 2017) is not currently applied in Canada. There is no formal system documenting structural impacts of wildland fire, but provincial/territorial fire management agencies typically keep records on these effects. To document major losses, there is the national Canadian Disaster Database (Public Safety Canada 2018).

While evacuations can prevent loss of life, an evacuation is also considered an impact. Evacuations disrupt daily life and are emotionally and financially expensive (McGee 2019; McGee et al. 2019). Evacuations can be very dramatic; in extreme situations, they can even prompt the formal declaration of a national disaster (Bowman et al. 2017). Many communities across Canada have experienced evacuations (Fig. 1*b*), with up to 88 000 people evacuated in a single event (Taylor et al. 2006; Ronchi et al. 2017; McLennan et al. 2018; McGee 2019). Some communities, particularly remote Indigenous communities, have been evacuated multiple times (Beverly and Bothwell 2011; McGee et al. 2019). Though most areas have community evacuation plans, evacuation capacity and efficiency have often not been properly evaluated. Ronchi et al. (2017) proposed an evacuation modeling framework that considers both fire spread and human movement components; this may provide a starting point for evacuation modeling in Canada. However, social perceptions related to evacuations (e.g., the willingness to leave) make evacuation modelling a very complicated topic (Cote and McGee 2014; Christianson 2015; Scharbach and Waldram 2016; McLennan et al. 2018; Asfaw et al. 2019*a*, 2019*b*; Christianson et al. 2019; McGee et al. 2019). There is some acknowledgement of alternatives to evacuations (e.g., stay and defend) being supported in Canada (Cote and McGee 2014; McLennan et al. 2018; McGee et al. 2019), but the comparative effects of varying strategies are unknown.

In addition to the sociological aspects of evacuation, a variety of studies have explored the social dimensions of wildland fire impacts (but see section 4.2.3). Topics include examining preferences and acceptance of wildland fire mitigation activities (McGee 2005; Faulkner et al. 2009; McGee et al. 2009; Harris et al. 2011; McFarlane et al. 2011; Labossière and McGee 2017) and the perceptions of values at risk (Christianson et al. 2014; Christianson 2015). Other sociological aspects central to determining impacts include trust (Shindler et al. 2014; McGee et al. 2016), risk communication (Boulianne et al. 2018; Hesseln 2018), decision-making processes (Sherry et al. 2019), and community resilience and recovery (Reimer et al. 2013). Human factors have been explored for the development, use, and benefits of fire danger rating (Taylor and Alexander 2006; Gould et al. 2013). Additionally, impacts on children and families (Botey and Kulig 2014; Townshend et al. 2015; Kulig et al. 2018) and on Indigenous communities (Christianson et al. 2012, 2013, 2014; Christianson 2015; Lewis et al. 2018) have recently been investigated.

For a risk assessment to include smoke, we need not only the likelihood of smoke emissions and the plume rise and dispersion, but also some measurement of the effects on human health over large areas involving a variety of smoke chemical components (Elliott et al. 2012; Henderson and Johnston 2012; Reisen et al. 2015). Smoke effects can be localized (e.g., firefighters at the fire or nearby towns) but can also affect locations at great distances, even in locations where direct effects of wildland fire are not experienced (Sigler et al. 2003; Reisen et al. 2015; Munoz-Alpizar et al. 2017). Furthermore, smoke can be the cause for evacuations (Beverly and Bothwell 2011; McGee et al. 2014; Council of Canadian Academies 2019) and can affect mental health and land-based livelihoods (Dodd et al. 2018; Council of Canadian Academies 2019). In Canada, emissions from wildland fires are used to provide air quality forecasts (Pavlovic et al. 2016). See Reisen et al. (2015) for a review of smoke and the tools available for smoke risk research and Goodrick et al. (2013) for a review of existing smoke transport models.

Even though negative impacts receive the majority of research focus, there has been considerable work done on the positive impacts of wildland fires. For example, in boreal and grassland ecosystems across Canada, fire is a crucial stand-renewing disturbance, triggering regeneration and creating habitat heterogeneity (Weber and Flannigan 1997; Brandt et al. 2013; McGee et al. 2014). Wildland fires and prescribed burns have also been shown to directly benefit human communities by reducing future fire risk (Muraro 1968) and promoting other land uses such as hunting, foraging, or farming (Pyne 2007; Gould et al. 2013; McGee et al. 2014; Christianson 2015). Another aspect of fire impacts that generally gets less attention is research of fire effects on a variety of values, other than direct effects on humans. In Canada, some work relating to these alternate effects has been undertaken, including: vegetation and ecology (Lynham et al. 1998; de Groot et al. 2003; Bergeron et al. 2004; Lecomte et al. 2006; Aubin et al. 2016; Stralberg et al. 2018; Boucher et al. 2019), wildlife habitat (Nappi et al. 2010; Stockdale et al. 2019), soil microbiota (Whitman et al. 2019), permafrost (Gibson et al. 2018), carbon (Amiro et al. 2001; Ohlson et al. 2006; de Groot et al. 2007; Kurz et al. 2008; Balshi et al. 2009; Wilkinson et al. 2018), fire management costs (Muraro 1968; Ohlson et al. 2006; Peter et al. 2006*a*; Hope et al. 2016; Stocks and Martell 2016), ecological services (Robinne et al. 2018), forestry

(Thompson et al. 2000; Armstrong 2004; Ohlson et al. 2006; Acuna et al. 2010; Savage et al. 2010; Girardin et al. 2013b; Raulier et al. 2013; Gauthier et al. 2014; Rijal et al. 2018), and the economy (Peter et al. 2006*b*; Flat Top Complex Wildfire Review Committee 2012; McGee et al. 2014).

3.2.1. Exposure

As discussed in section 2.1.3, the metric selected to quantify exposure will depend on the value under consideration. In Canada, only exposure of structures has been studied in some detail using experimental, observational, and modelling contexts. Physical models along with data collected at the International Crown Fire Experiment in the Northwest Territories (Stocks et al. 2004) indicate that structures are highly unlikely to ignite from radiative heat if they are sufficiently separated from the flaming front (e.g., 30 m), as exposure to this heat transfer process is limited at greater distances (Cohen 2004). Exposure to structures from spotting, however, is considered the primary process relevant to structure ignition and is supported by observations (Schroeder 2010; Hvenegaard et al. 2016; Westhaver 2016). This is reflected in the focus of interface exposure modelling (Beverly et al. 2010; BC Wildfire Service 2017; Johnston and Flannigan 2018). Furthermore, there are indications that fuel treatment can reduce exposure and aid suppression efforts (Beverly et al. 2010; Schroeder 2010; Hvenegaard et al. 2016; Wilkinson et al. 2018).

3.2.2. Estimating impacts

To determine impacts of wildland fires, it is essential to include the exposure, the effects of that exposure (which is dependent on susceptibility of the values), and some quantification and valuation of the associated impacts. Ultimately, impacts are judged by the change in net value (B_{ij}–L_{ij} from eq. 2, section 2.1.2). Ohlson et al. (2006) suggested that the selection of parameters to be judged (see Table 2 for available data) and how to quantify them (e.g., with a dollar value or otherwise) may be guided by expert opinion and data availability and it is often possible to use proxies. The choice of what to include in values maps for fire management agencies, and the policies prioritizing different types of values (e.g., human life, communities, harvesting areas), is largely based on expert opinion (Ohlson et al. 2003; Ontario Ministry of Natural Resources 2013; BC Wildfire Service 2017; McFayden et al. 2019; Saskatchewan Wildfire Management Branch 2019). Exposure can also be estimated using probabilistic methods (e.g., Haas et al. 2013; Miller and Ager 2013; Scott et al. 2013; Evers et al. 2019), and subsequently impacts of such exposure can be estimated.

Previous impact estimation done outside of Canada often aggregates effects as the net value change (NVC; FAO 1986) over a range of exposure levels, with this dose–response relationship described by a "response function" (e.g., Fairbrother and Turnley 2005; Calkin et al. 2010; Miller and Ager 2013; Scott et al. 2013). Response functions can be derived from statistical methods based on observations (e.g., as shown by Alexander et al. (2007) for observations of house survival) or existing models (e.g., structure ignition models or fire effects models; Miller and Ager 2013). Response functions may also be derived from expert opinion using an assortment of techniques. Cost-benefit analysis such as the least cost plus damage model (Sparhawk 1925) can be used to evaluate and assign importance to the positive and negative costs obtained from expert opinion. Alternatively, multiple criteria model (MCM) techniques can reach the same goal of providing a relative importance of NVC, but without establishing monetary amounts for values (Chen et al. 2003; Ohlson et al. 2006; Scott et al. 2013). These MCM techniques can also be referred to as multi-attribute trade-off analysis or multi-criteria decision-making. These techniques can include analytic hierarchy process, maximum-difference conjoint analysis, multi-attribute utility theory, and fuzzy set theory (Zimmermann 2010; Hanewinkel et al. 2011). Several of these techniques have been used in Canada in research and fire management valuation (e.g., Ferrier and Haque 2003; Lee and Kant 2006; Ohlson et al. 2006; Beverly et al. 2008; Tutsch et al. 2010; Gould et al. 2013; McFayden et al. 2019). Regardless of trade-off or ranking technique, all methods using expert opinion require some process to extract those opinions and preferences. There are a variety of methods available to efficiently assess preferences (e.g., the Deliphi method; see White 1995 for a thorough review).

3.3. Future risk

Considering the increasing occurrence of climatic extremes, the potential for unrestrained warming (Steffen et al. 2018), and self-promoting carbon feedbacks (Price et al. 2013; Oris et al. 2014), future fire activity may see a transition not just to a new state where our current extreme fire years are average fire years (i.e., not just to a so-called new normal) but to a system with increasingly variable and extreme fire activity. The predicted changes are uncertain and variable across locations, but they suggest that overall fire activity will be different from what has occurred in recent history (Flannigan et al. 2009; Coogan et al. 2019). For most areas of Canada, climate may become more prevalent as a driver of fire activity (Pechony and Shindell 2010; Krawchuk and Cumming 2011). The effects of climate change will include a general increase in variation and extremes in weather (e.g., increased temperatures, more frequent dry periods, increased storms and lightning), which is largely predicted to increase future fire activity within Canada (Krawchuk et al. 2009*a*; Wotton et al. 2010, 2017; Price et al. 2013; Woolford et al. 2014; Jolly et al. 2015; Flannigan et al. 2016; Wang et al. 2017; Boulanger et al. 2018). Changes in fire activity have already been observed (Podur et al. 2002; Coops et al. 2018; Hanes et al. 2019), and recent results suggest that extreme fire weather and behaviour are 1.5–6 times more likely due to anthropogenic emissions (Kirchmeier-Young et al. 2017). Furthermore, climate change impacts on fire will increasingly interact with those of other natural disasters (e.g., heatwaves, flooding, and fires), with the potential for cascading effects on physical infrastructure (Council of Canadian Academies 2019).

Fuels may change in the future due to human development and land use (Krawchuk et al. 2009*a*; Gralewicz et al. 2012*a*; Bistinas et al. 2013), resulting in changes in fire risk. Additionally, effects of climate change on fuels may include species range shifts (Gauthier et al. 2015; Aubin et al. 2018) and changes in fuel consumption, loads, types, or arrangement (de Groot et al. 2013; Lehsten et al. 2016; Stralberg et al. 2018; Boucher et al. 2019). However, biotic interactions (Johnstone and Chapin 2006; Krawchuk and Cumming 2011; Erni et al. 2018; Stralberg et al. 2018) or changed albedo of post-fire landscapes (Randerson et al. 2006) and local climate change impacts (Krawchuk et al. 2009*b*; Boulanger et al. 2014) may limit the positive feedback of fires on climate change (Price et al. 2013; Oris et al. 2014; Chaste et al. 2019). Pest outbreaks will also be a factor influencing future fire risk, with climate change resulting in potentially large buildups of dead fuels to burn (Dale et al. 2001; Fleming et al. 2002; Price et al. 2013; Perrakis et al. 2014).

Impacts on human population, structures, and infrastructure will also see future changes. Canada's population is growing (Statistics Canada 2019), but most of this growth is in dense urban centres with little direct wildland fire risk (Peter et al. 2006*a*; Fig. 1). Urban sprawl and increased recreational property development (Peter et al. 2006*a*) may end up increasing the amount of interface and the number of structures and population living at risk (McGee et al. 2014; Hope et al. 2016; Knorr et al. 2016; Johnston and Flannigan 2018). Recently, isolated communities and, in particular, Indigenous communities on reserves, have experienced escalated population growth (Peter et al. 2006*a*; Statistics Canada 2019). This trend is particularly worrying with respect to fire risk, as these communities may already be more at risk due to their location. Notably, a high proportion of Indigenous communities are within the wildland–urban interface area (Christianson 2015; McGee et al. 2019).

Changes to fire risk in the future will have potentially drastic impacts on fire management in Canada. Current research has focused on how shifting fire seasons or increases in fire activity will impact fire management expenditures. Recent evidence suggests that those rare bad fire years for extreme fire suppression spending will become more frequent, perhaps occurring every other year (Hope et al. 2016). There is increasing evidence that in addition to continued rising costs, future climate-driven changes to fire activity will exceed the current response capacity (Stocks and Martell 2016). Suppression capacity is particularly susceptible to being overwhelmed when there are multiple fires burning at once; this can result in large, escaped fires (Hirsch et al. 2001; Cumming 2005; de Groot et al. 2013). Escaped fires are predicted to increase up to 92% by the end of the century in the province of Ontario (Podur and Wotton 2010), requiring an unrealistic doubling of agency capacity to keep pace (Wotton and Stocks 2006). Furthermore, climate change effects also have the implication that there will be more extreme fire weather, resulting in more days with unmanageable fire (Wotton et al. 2017) or more spread days (Wang et al. 2017) across the country. Overall, the apparent control we have over fire may partially explain why we are more focused on fire suppression than we are on predicting and adapting to fire as a natural hazard as with earthquakes or hurricanes (Dale et al. 2001; McCaffrey 2004; Maranghides and Mell 2012; Moritz et al. 2014).

4. Future directions

There are a variety of stakeholders with an interest in wildland fire risk in Canada, including forest-dependent industries, insurance companies, railways, utilities, communications, multiple levels and branches of federal and provincial/territorial governments, academic institutions, First Nations bands and Tribal Councils, municipalities, environmental groups, and individual community members. This diversity of players indicates that the research needs and risk-management decisions will not be uniform across the country, particularly in such a large country with diverse landscapes. No one stakeholder group can reasonably be expected to address and manage all aspects of fire risk; effective collaboration and integration of multi-disciplinary efforts with differing perspectives is essential. For example, experiential knowledge, traditional knowledge, and cross-discipline scientific knowledge can weave together to form a much more effective approach (Ferrier and Haque 2003; Miller and Ager 2013; Sherry et al. 2019).

4.1. Fire risk assessment

The "likelihood and impacts" model of risk provides a template for a comprehensive view of risk. The next logical step in studying Canada's wildland fire risk is the development of tools to support comprehensive risk assessments. These tools can take on a variety of forms, but foremost of these is the development of a formal quantitative risk framework, similar to what exists in the United States (Scott et al. 2013), using strategies from ecological risk assessment (Fairbrother and Turnley 2005; Suter 2006; Ager et al. 2012; Robinne et al. 2018) or systems analysis (White 1995). Looking to existing tools can provide guidance or can be adapted to the Canadian context. Capitalizing on existing methods used in other natural hazards could prove useful, as could application of ideals from high-level risk-management frameworks such as Canada's national emergency strategies (Public Safety Canada 2009; Public Safety Canada 2017) or the United Nations' Sendai Framework for Disaster Risk Reduction (UNISDR 2017). Coordinating with existing works done on risk assessment would also promote segue to a multi-hazard approach to risk assessment (Hanewinkel et al. 2011; Lyle and Hund 2017; Newman et al. 2017). Complexities arising from assessing and managing risk with various relevant temporal and spatial scales (Chen et al. 2003; Fairbrother and Turnley 2005; Hanewinkel et al. 2011; Scott et al. 2013; Ager et al. 2017), along with the diversity of values that may be included in a risk assessment (Scott et al. 2013), suggests that a modular system with explicit consideration of scale may be ideal. Focus should be on a highly adaptable holistic system, avoiding the development of a multitude of ad hoc and oversimplified tools (which has been pointed out as a factor limiting the potential of the US approach; Thompson and Calkin 2011; Hyde et al. 2013; Miller and Ager 2013; Chuvieco et al. 2014). In fact, the development of a coordinated Canadian risk-assessment framework has recently been identified as a priority to be addressed (Sankey 2018).

Though risk assessment can feed scientific research endeavours, the needs within fire risk management should be the guiding principle behind development. Ideally, priority should be placed on integration with existing systems including fire decision support or agency-specific risk frameworks (Ohlson et al. 2003; Ontario Ministry of Natural Resources 2013; BC Wildfire Service 2017; Saskatchewan Wildfire Management Branch 2019). Ultimately, fire risk assessments could become fully integrated in operational fire management decision support (Wei et al. 2019). Inclusion of not just the multiple interacting physical and biological relationships, but also the social dimensions of risk will support a much more realistic framework (Simard 1977; Cutter et al. 2003; Ferrier and Haque 2003; Hanewinkel et al. 2011). Crucial considerations for a risk framework also include validation, sensitivity analysis, and inclusion of a way to account for uncertainty (White 1995; Miller and Ager 2013; Newman et al. 2017).

A practical risk-assessment system would support "risk-informed" decision-making (Calkin et al. 2011), where managing risk is a highly uncertain and dynamic system (Simard 1977). Ultimately, the goal is to use risk assessment in applied risk management (Finney 2005; Newman et al. 2017; Wei et al. 2019). It should be noted, however, that even the best designed risk assessment does not provide all the answers or remove all the risk (i.e., residual risk; ISO 2009; Thompson et al. 2016a), but it can better manage trade-offs in a tractable way and help risk managers be more effective. There is an urgent need to start the intimidating task of risk assessment, despite the complexity, knowledge gaps, and limitations (section 4.4).

4.2. Foundational fire risk research

Continued focus on building upon the existing wildland fire knowledge is essential for the advancement of fire risk research. Data for all aspects of fire risk is a limitation (section 4.2.1), and there are many multi-disciplinary research opportunities within fire behaviour (section 4.2.2), the human dimensions of risk (section 4.2.3), and more diverse fire effects (section 4.2.4). Investment in better understanding the fundamentals of fire may help to reduce the extensive data requirements through a better grasp of data scaling and analysis capabilities. Some knowledge of future conditions (section 3.3) will also be essential to guide research priorities in support of fire risk knowledge. Risk research will benefit from continued investment in studying climate change, fuel changes, human developments, and pressures to fire management.

4.2.1. Data

Analysis of risk can be data-intensive. Within Canada, there are sufficient data available for preliminary assessments of risk (Table 2); however, data can be inadequate for even some basic inputs required for fine-scale or comprehensive risk assessments. Existing data are restrained by spatial resolution (e.g., the 250 m national fuels layers; Simpson 2014), temporal extent (e.g., the National Fire Database only reliably goes back to the 1980s; Taylor et al. 2013; Hanes et al. 2019; Xi et al. 2019), and classification issues (e.g., the forest resource inventory; Braun et al. 2010). Limited data support sociological, indirect, and interactive effects. Furthermore, traditional and experiential knowledge as a data source is currently underused (Stocks and Wotton 2006; Christianson 2015; Coughlan et al. 2018). Detailed local-scale data are lacking, including fuels (Mell et al. 2010), exposure (Maranghides and Mell 2012; Caton et al. 2017), detailed structural locations and characteristics (Davidson 2013), impacts (Beverly and Bothwell 2011), weather (MNP 2017), and human population (Johnston and Flannigan 2018). There is also a need for national data consistency (Calkin et al. 2010) and data standards (e.g., as in the Sendai Framework; UNISDR 2017).

Computing power has increased rapidly, allowing more detailed or larger-scale analysis, and also allowing the use of more advanced data-hungry techniques (Gralewicz et al. 2012*b*; Taylor et al. 2013; Krawchuk and Moritz 2014; Thompson et al. 2016*b*; Boulanger et al. 2018; Xi et al. 2019). Models may provide an appropriate platform to combine the multiple knowledge systems and varied disciplines to assess risk in an increasingly realistic way (Chapin et al. 2003; Bowman et al. 2011; Eiser et al. 2012; Gralewicz et al. 2012*b*; Brandt et al. 2013; Gauthier et al. 2014; Moritz et al. 2014; Fischer et al. 2016; Aubin et al. 2018).

4.2.2. Fire behaviour

Studying fire itself using a combination of approaches (e.g., lab, field, and modelling techniques; Ager et al. 2011; Mell et al. 2010) and leveraging new technologies (e.g., LiDAR and infrared observations; Hyde et al. 2013) will substantially improve our core fire behaviour knowledge. Any further study of fire behaviour will support better analysis of risk and also enhance monitoring and detection (Price et al. 2013; Gauthier et al. 2014; Caton et al. 2017; Johnston et al. 2017, 2018; Coops et al. 2018). There are still crucial gaps in our fire behaviour knowledge that will need to be addressed to fully quantify risk in Canada. Some of these include:

- fire behaviour state transition, such as the transition from surface to crown fire (Cruz et al. 2003; Miller and Ager 2013; Caton et al. 2017)
- detailed physics-based observations (Mell et al. 2010; Hyde et al. 2013)
- firebrand production (size, distribution, flux) and spotting ignition in wildland fuels (Caton et al. 2017)
- structure ignition and structure-to-structure ignition (Mell et al. 2010; Miller and Ager 2013; Caton et al. 2017)
- interface fire behaviour relevant to structure exposure (Stocks and Wotton 2006; Beverly et al. 2010; Mell et al. 2010; Maranghides and Mell 2012; Caton et al. 2017; Johnston and Flannigan 2018) and better characterization of exposure conditions for effective mitigation (Evers et al. 2019)
- fire behaviour in novel or changing fuels including peatlands, urban fuels, and fuel treatment areas (e.g., thinning, removal or ladder fuels) (Mell et al. 2010; Price et al. 2013; Bar-Massada et al. 2014; Reisen et al. 2015; Hvenegaard et al. 2016; Gibson et al. 2018; Wilkinson et al. 2018; Thompson et al. 2019)
- pest- or disease-damaged fuels (Forestry Canada Fire Danger Group 1992; Fleming et al. 2002; Perrakis et al. 2014; James et al. 2017; Coogan et al. 2019)

Improvements of fire behaviour knowledge can improve the FBP System (Gould et al. 2013) and risk-assessment endeavours in general. Additionally, more research is needed on how fuel treatments, prescribed burning, fire suppression, and other actions taken to mitigate risk (section 4.3) impact fire behaviour. Those impacts then need to be incorporated into risk assessments to support appropriate actions and optimize costs (Muraro 1968; Ohlson et al. 2006; Stocks and Wotton 2006; Parisien et al. 2007; Beverly and Bothwell 2011; Coogan et al. 2019).

4.2.3. Human dimensions of fire risk

Most research on wildland fire risk has focused on its physical components, largely neglecting the social, political, economic, and cultural aspects (Pyne 2004). It has been argued that social aspects of fire should not merely be a direct effect considered in risk calculations, but central to the main risk determination (Ferrier and Haque 2003; Finney 2005; Pyne 2007; Eiser et al. 2012), as humans define and evaluate the risk, perceive the risk, and even create the risk. To comprehensively quantify fire risk and for improved community disaster management, the sociological aspects of fire and the human dimensions of fire risk must be addressed. There are a wide variety of topics that require further research; specifically, these include:

- physical and mental health of residents and first responders (Sankey 2018; Coogan et al. 2019)
- appropriate actions to reduce fire risk in the context of local communities; including approaches to improve preparation, evacuations, evacuation alternatives, and rebuilding (Beverly and Bothwell 2011; Cote and McGee 2014; Christianson 2015; McLennan et al. 2018; Sankey 2018)
- risk perception and the sociological aspects of implementing risk mitigation activities (Stocks and Wotton 2006; McGee et al. 2009; McFarlane et al. 2011; Eiser et al. 2012; Toman et al. 2013; Westhaver 2015; Sankey 2018; Sherry et al. 2019)
- improved understanding of the coupled human/fire system including political, economic, ecological, and social aspects of fire activity and risk (Stocks and Wotton 2006; Liu et al. 2007; Bowman et al. 2011; Tedim et al. 2018)
- sociological aspects of vulnerability and adaptive capacity with respect to communities (in particular, remote and Indigenous communities) and individuals (in particular, elderly, disabled, or less financially stable individuals) (Ferrier and Haque 2003; Gaither et al. 2011; Christianson 2015; Wigtil et al. 2016; Council of Canadian Academies 2019)
- further development of methods for valuation and quantification of a wider variety of impacts assessed under differing priorities and perspectives of risk (Ferrier and Haque 2003; Calkin et al. 2010; Zimmermann 2010; Hanewinkel et al. 2011; Christianson 2015; McFayden et al. 2019)
- application of knowledge gained from international social science research (McCaffrey and Olsen 2012; Toman et al. 2013) and from experiential and traditional knowledge (Ferrier and Haque 2003; Bowman et al. 2011; Christianson 2015; Miller and Aplet 2016; Sankey 2018; Sherry et al. 2019)

4.2.4. Research for a variety of effects

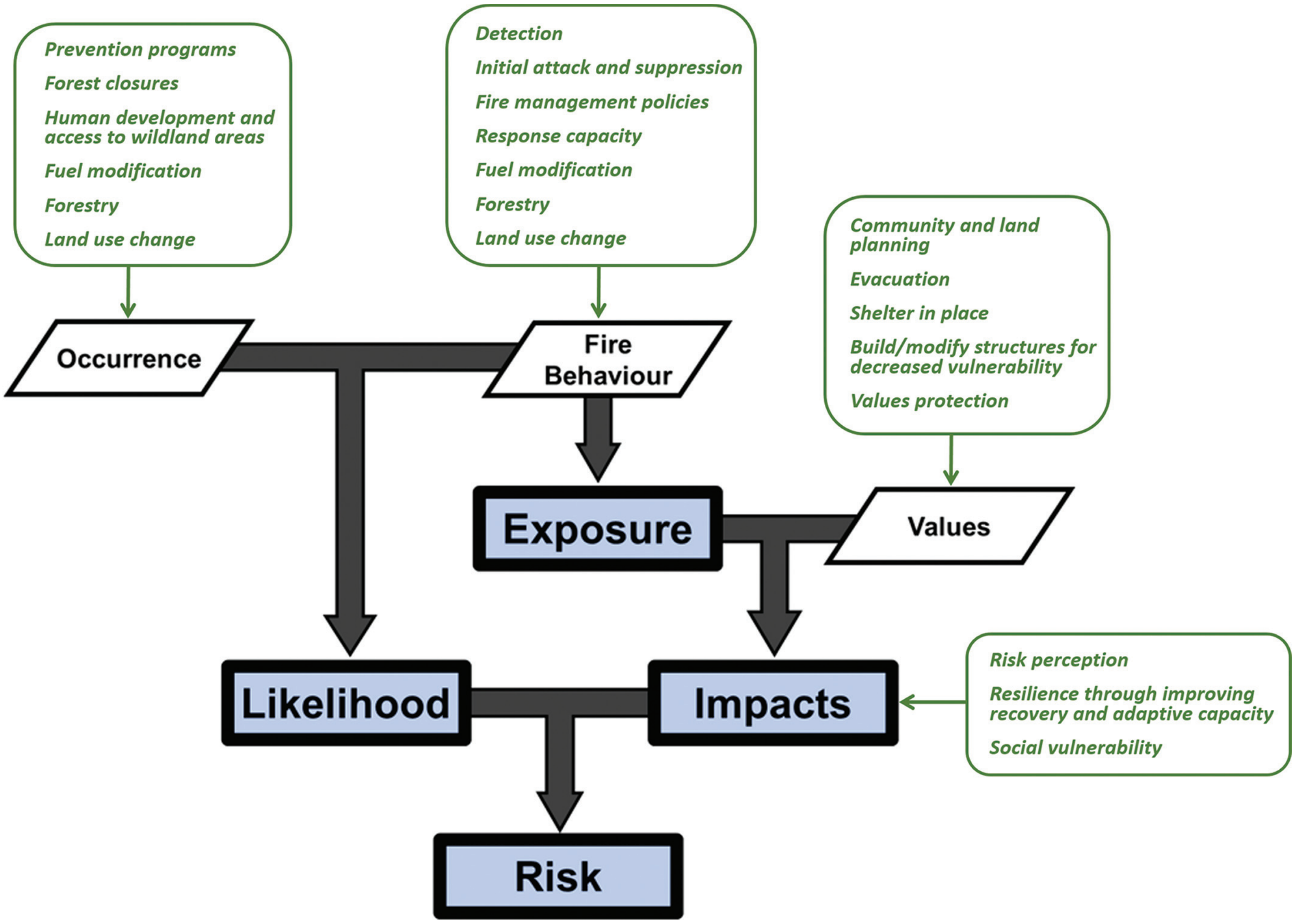
We have limited knowledge of the possible effects of wildland fires to determine vulnerabilities, impacts, and resilience in a comprehensive risk assessment. More information is required on a wider variety of effects, including:

- carbon effects (Stocks and Wotton 2006; Hurteau et al. 2008; Hyde et al. 2013)
- smoke emissions, transport, and effects (Mell et al. 2010; Reisen et al. 2015; Pavlovic et al. 2016; Caton et al. 2017; Council of Canadian Academies 2019; Coogan et al. 2019)
- faunal habitat, particularly for rare or sensitive species (Hyde et al. 2013; Stockdale et al. 2019)
- fire effects (and their interactions) involving vegetation, soil, water, and atmosphere (Fairbrother and Turnley 2005; Chuvieco et al. 2010; de Groot 2010; Thompson et al. 2011; Hyde et al. 2013; Miller and Ager 2013; Gauthier et al. 2015; Fischer et al. 2016; Robinne et al. 2018; Coogan et al. 2019)

4.3. Risk management

Risk assessment, the first step of risk management, can inform decisions when aiming to reduce negative impacts and promote positive impacts of fire (White 1995; Finney 2005; Calkin et al. 2014). As Finney (2005, pp. 105–106) stated, "…wildland fires are inevitable. The ecological consequences of fires and the susceptibility of human values, however, are not inevitable because man-

Fig. 7. Examples of potential risk management options for wildland fire (green text) in relation to components of fire risk to human populations and structures.



agement activities can be undertaken to change these outcomes." Wildland fire risk management has informally been ongoing since humans started using fire and experiencing impacts from fire (Simard 1977; Finney 2005). However, formal risk management as a system is much less common in fire than in other disciplines (e.g., insurance, business).

Management of fire risk can manifest in a variety of ways (Fig. 7), such as using fuel management to reduce extreme fire behaviour, preventing unwanted human-caused fires, and implementing fire suppression to slow or stop the spread of a fire (Muraro 1968; Simard 1977; Finney 2005; Mell et al. 2010; Wotton et al. 2017). The negative impacts of a fire can be moderated through evacuations to avoid injuries or loss of life (Beverly and Bothwell 2011; Ronchi et al. 2017), building or modifying structures for fire-resistance (Cohen 2004; Faulkner et al. 2009; Mell et al. 2010), enhancing redundancy and resiliency of critical infrastructure (Public Safety Canada 2009), investment in protecting groups who are particularly vulnerable due to social or health issues (e.g., isolated communities and the elderly) (Ferrier and Haque 2003; Gaither et al. 2011; Gauthier et al. 2014; Christianson 2015), or implementing fire management policies that allow fires to burn when it is ecologically beneficial or would reduce the need for either fuel treatments or prescribed burning.

Many options are available to mitigate wildland fire risk and are not limited to those mentioned here. There will not be one solution to reducing risk; multiple actions may be taken, and not all actions will be appropriate for every area (Beverly et al. 2010; Alcasena et al. 2015; Evers et al. 2019). This highlights the importance of evaluating the existing strategies related to preparedness, mitigation, response, recovery, and adaptive capacity to manage risk. Research into methods to promote adoption and effective implementation of risk-management strategies has the potential to reduce risk. For example, one risk-management response may include the use of FireSmart (Partners in Protection 2003) principles to reduce structure ignition vulnerability (Cohen 2004; Faulkner et al. 2009; Calkin et al. 2014; Westhaver 2016). The actual implementation of FireSmart principles could include grass roots community initiatives, large-scale collaboration and coordinated promotion of the program, economic incentives (from government or insurance), or implementation of building codes and land development guidelines for better wildland fire resistance (Partners in Protection 2003; Westhaver 2016; Sankey 2018). Additionally, effective communication of the risk-management options and uncertainties is essential (Partners in Protection 2003; McCaffrey and Olsen 2012; Miller and Ager 2013; Steelman and McCaffrey 2013; Toman et al. 2013; Sherry et al. 2019).

Wildland fire faces an interesting future with potential for drastic change and increasing pressures on fire management (section 3.3). In addition, risk management will also have to incorporate uncertainty, complex interacting hazards, and novel dynamics (Simard 1977; Ferrier and Haque 2003; Pechony and Shindell 2010; Boulanger et al. 2018; Council of Canadian Academies 2019). Further research and the application of new approaches addressing the challenges faced in fire management are essential (Coogan et al. 2019), considering the potential for rapid changes and the fact that it is unrealistic and undesirable to fight every fire (Podur and Wotton 2010; Price et al. 2013; Hope et al. 2016; Cardil et al. 2019). Pyne (2007, p. 465) found the perfect words to summarize this: "As they scanned the future, members of the Canadian fire community saw more fire and less certainty about how to respond."

4.4. Limitations

In this review, we have not developed a formal comprehensive risk framework, performed a detailed systematic review of the fire research literature, nor provided strict directives for fire research or management. Rather, we focused on core issues pertaining to quantifying wildland fire risk in the Canadian context. This paper is not without bias; we are primarily scientists and fire managers viewing fire risk issues based on our experiences with fire (Eiser et al. 2012). We also admittedly focus more on issues relevant to the direct impacts on humans and less on the ecological, sociological, and indirect risk aspects. These suggestions for thinking and estimating risk are just that, suggestions; there are a variety of approaches.

It should be noted that all the existing research we have summarized are not without limitations or errors, and there is much left to learn. Furthermore, caution should be used when applying research results to real-world situations, using simple tools to inform complex questions (Taylor and Alexander 2006), or assuming past relationships will be analogous to the future. For example, the use of historic data should be considered with the caveat that past fire risk may not be analogous to risk under current or future conditions; humans have built new communities, suppressed fires, harvested forests, and changed the climate (Donovan et al. 2007; Hanewinkel et al. 2011; Eiser et al. 2012; Bar-Massada et al. 2014; Krawchuk and Moritz 2014; Xi et al. 2019).

5. Conclusion

Understanding wildland fire risk will be crucial in addressing a major challenge Canada is faced with: how to live with fire in a fire-prone country. To understand and characterize risk from this complex and unavoidable natural hazard, a diversity of management approaches, scientific disciplines, and knowledge systems must be integrated within a framework that accounts for the uncertainty associated with how wildland fire interacts with the environment. In this paper, we consolidate existing wildland fire risk research in the distinctive context of fire in Canada using consistent terminology and the "likelihood and impacts" definition of risk. Overall, the aim is to provide a starting point for comprehensive risk assessments and a formal quantitative risk framework. We trust that by establishing a more rigorous way to assess fire risk, we can both limit the negative outcomes and promote the positive outcomes of current and future wildfire activity.

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Appendix A. Wildland fire risk from the literature

Table A1. Definitions of fire risk and several terms that are often used in place of fire risk in the wildland fire literature.

Term	Definition
Fire risk	The product of potential impacts from wildland fire and the likelihood of those impacts occurring (Bachmann and Allgöwer 2000; Finney 2005; Calkin et al. 2010).
Fire occurrence	Can be represented by the number of fires, area burned, ignition occurrence (see below), fire frequency, burn cycle, or fire return interval; does not include a measure of likelihood or potential impacts (Finney 2005).
Ignition occurrence	Instance of fire ignition or probability of ignition; despite a legacy of use as equivalent to risk, it does not follow the full “likelihood and impacts” definition of risk (FAO 1986; Hardy 2005; Wotton 2009).
Fire hazard	Multiple definitions are used: (*a*) the more static physical characteristics of the fuel complex (i.e., structure, composition, arrangement) that determine the potential fire behaviour, it does not include the dynamic fuel moisture changes (CIFFC 2003; Wotton 2009; Chuvieco et al. 2014); (*b*) the potential for harm, considering the exposure to fire and possible effects but no accounting for likelihood (Simard 1977; Ferrier and Haque 2003; ISO 2009; Miller and Ager 2013); (*c*) the potential for harm considering the likelihood and fire intensity (Scott et al. 2013; Stockdale et al. 2019; Xi et al. 2019); or (*d*) the fire itself when generally referring to fire as a natural hazard (Bachmann and Allgöwer 2001; UNISDR 2017).
Burn probability	Likelihood of fire burning a given location (Parisien et al. 2005), represents just the likelihood side of the risk model.
Exposure	The incoming “thermal insult” (Caton et al. 2017) experienced by a value based on its location, irrespective of its resistance to the potential impacts of that exposure (Beverly et al. 2010; Maranghides and Mell 2012; Miller and Ager 2013).
Fire severity	Degree of loss of organic matter, or a measure of ecosystem impacts of a fire (Keeley 2009).
Fire danger	Often using an index, a characterization of the potential for ignition and spread of a fire and indicates difficulty of control; it does not include likelihood or impacts (Bar-Massada et al. 2009; Wotton 2009; Chuvieco et al. 2010; Miller and Ager 2013).