

# Scientists' warning on wildfire — a Canadian perspective

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**Abstract:** Recently, the *World Scientists' Warning to Humanity: a Second Notice* was issued in response to ongoing and largely unabated environmental degradation due to anthropogenic activities. In the warning, humanity is urged to practice more environmentally sustainable alternatives to business as usual to avoid potentially catastrophic outcomes. Following the success of their warning, the Alliance of World Scientists called for discipline-specific follow-up papers. This paper is an answer to that call for the topic of wildland fire. Across much of Canada and the world, wildfires are anticipated to increase in severity and frequency in response to anthropogenic activities. The world scientists' second warning provides the opportunity for wildland fire researchers to raise the profile of the potential impacts that anthropogenic activities are likely to have on future fire regimes and, in return, what impacts future fire regimes may have on humanity. We discuss how wildfire is related to several issues of concern raised in the world scientists' second warning, including climate change, human population growth, biodiversity and forests, and freshwater availability. Furthermore, we touch on the potential future health impacts and challenges to wildfire suppression and management in Canada. In essence, our wildfire scientists' warning to humanity is that we, as a society, will have to learn to live with more fire on the landscape. We provide some recommendations on how we might move forward to prepare for and adapt to future wildfire regimes in Canada. Although this paper is primarily Canadian in focus, the concepts and information herein also draw from international examples and are of relevance globally.

**Key words:** climate change, wildfire, wildland fire, world scientists' warning.

**Résumé :** Récemment, le « *World Scientists' Warning to Humanity : a Second Notice* » a été publié en réaction à la dégradation de l'environnement qui se poursuit quasiment sans relâche à cause de l'activité humaine. Dans cette mise en garde, l'humanité est instamment priée d'adopter des pratiques alternatives plus durables du point de vue environnemental que les pratiques actuelles pour éviter des conséquences potentiellement catastrophiques. Étant donnée le succès de leur mise en garde, le « Alliance of World Scientists » a lancé un appel à contribution en sollicitant des articles de suivi disciplinaires. Cet article constitue une réponse à cet appel à contribution pour le domaine des feux de forêt. Dans la majeure partie du Canada, et du monde, on prévoit que la sévérité et la fréquence des feux de forêt ira en augmentant à cause de l'activité humaine. Le deuxième avertissement des scientifiques du monde fournit l'occasion aux chercheurs dans le domaine des feux de forêt de mieux faire connaître les impacts que l'activité humaine pourrait vraisemblablement avoir sur les futurs régimes des feux et, en retour, quels impacts les futurs régimes des feux pourraient avoir sur l'humanité. Nous discutons de la façon dont les feux de forêt sont reliés à plusieurs sujets de préoccupation soulevés par la deuxième mise en garde des scientifiques à travers le monde, incluant les changements climatiques, la croissance de la population humaine, la biodiversité et les forêts ainsi que la disponibilité de l'eau douce. De plus, nous abordons les impacts sur la santé et les défis potentiels à venir posés par la gestion et la suppression des feux de forêt. Essentiellement, notre mise en garde pour l'humanité en tant que spécialistes des feux de forêt est que nous aurons, comme société, à apprendre à vivre avec plus de feux dans le paysage. Nous formulons certaines recommandations sur la façon dont nous pourrions aller de l'avant pour se préparer et s'adapter aux futurs régimes des feux au Canada. Bien que principalement axés sur le Canada, les concepts et l'information présentés dans cet article s'inspirent aussi d'exemples internationaux et sont pertinents à l'échelle mondiale. [Traduit par la Rédaction]

**Mots-clés :** changement climatique, feu de forêt, feu de végétation, avertissement des scientifiques à travers le monde.

## 1. Introduction

In 1992, the [Union of Concerned Scientists \(1992\)](#) along with more than 1700 independent scientists drafted and signed the *World Scientists' Warning to Humanity*, which pleaded with people and institutions to take action towards reducing environmental degradation. Recently, the Alliance of World Scientists released a follow-up *World Scientists' Warning to Humanity: a Second Notice* ([Ripple et al. 2017](#); hereafter referred to as the “second warning”) based on the original manifesto produced over 25 years ago. The second warning reiterated the concerns raised in the first warn-

ing, including stratospheric ozone depletion, freshwater availability, marine life diminution, ocean dead zones, forest loss, biodiversity reduction, climate change, and human population growth. Of concerns raised in the first warning, the stabilization of the stratospheric ozone layer was the only challenge considered successfully addressed. Meanwhile, the consensus is that the other issues raised have grown worse ([Intergovernmental Panel on Climate Change \(IPCC\) 2014](#); [Ripple et al. 2017](#)).

Similarly, wildland fire researchers have for decades raised concerns about the potentially catastrophic and interactive impacts of human activities on fire regimes, including anthropogenic

Received 15 March 2019. Accepted 27 May 2019.

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**Table 1.** A selection of papers investigating the impacts of climate change on aspects of fire regimes in Canada and elsewhere and observed Canadian trends.

Fire regime metric	References
<b>Predicted effects</b>	
Fire weather	Beer and Williams 1995; Flannigan et al. 1998; Miller and Schlegel 2006; Moriondo et al. 2006; Malevsky-Malevich et al. 2008; Bedia et al. 2015
Fire danger rating	Flannigan and Van Wagner 1991; Bergeron and Flannigan 1995; Flannigan et al. 2000; Amiro et al. 2001; Williams et al. 2001; Kochtubajda et al. 2006; Pitman et al. 2007; Liu et al. 2010; Flannigan et al. 2013; Wang et al. 2015
Area burned	Price and Rind 1994; Weber and Flannigan 1997; Flannigan et al. 2005, 2009a, 2009b; Cary et al. 2006; Podur and Wotton 2010; Wimberly and Liu 2014; Bedia et al. 2015; Wu et al. 2015
Spread days	Wang et al. 2017
Intensity	de Groot et al. 2013; Wotton et al. 2017
Season length	Wotton and Flannigan 1993; Weber and Flannigan 1997; Flannigan et al. 2009a, 2013; Bedia et al. 2015
Lightning ignitions	Price and Rind 1994; Romps et al. 2014
Fire size	Westerling et al. 2011; Barbero et al. 2015
Occurrence or frequency	Weber and Flannigan 1997; Flannigan et al. 2009a, 2009b; Krawchuk et al. 2009; Westerling et al. 2011; Moritz et al. 2012; Rocca et al. 2014
Severity	Weber and Flannigan 1997; Flannigan et al. 2013
Fire-mediated ecosystem change	Weber and Flannigan 1997; Stralberg et al. 2018
<b>Observed trends</b>	
Area burned	Gillet et al. 2004; Dennison et al. 2014; Abatzoglou and Williams 2016; Coops et al. 2018; Hanes et al. 2019
Season length	Jolly et al. 2015; Jain et al. 2017; Hanes et al. 2019
Lightning ignitions	Woolford et al. 2014; Veraverbeke et al. 2017; Hanes et al. 2019
Fire size	Hanes et al. 2019

climate change (Flannigan and Van Wagner 1991), the growing wildland–human interface (Robinne et al. 2016), insect outbreaks (Page et al. 2012), historic fire suppression (Steel et al. 2015), and forest conversion to more flammable species (Gómez-González et al. 2018). Recent observed changes in wildland fire activity may be the most compelling indicators of the impacts of ongoing environmental changes on forests. The 2017 fire season saw many high-profile fire events in Canada (British Columbia (BC), Alberta, Northwest Territories, Saskatchewan, Manitoba), USA (e.g., the “Mendocino Complex” and “Tubbs” fires in California), and across the world, including in Chile, Portugal, Spain, South Africa, Ireland, and even Greenland. This was followed in 2018 by extreme or noteworthy fire seasons in Greece, England, Sweden, and North America, including Ontario and back-to-back seasons in BC and California. The 2018 fire season in BC was the worst on record (CBC 2018), exceeding the ~1 210 000 ha burned in 2017 (Government of British Columbia 2019). In California, the largest (“Mendocino Complex”; ~185 800 ha), the most destructive (“Camp Fire”; 18 804 structures), and the deadliest (“Camp Fire”; 86 fatalities) fires on record occurred in 2018 (Cal Fire 2019). The weight of evidence suggests that recent catastrophic fires in these regions are not merely outliers, but rather indications of what the future holds (e.g., Bedia et al. 2015; Yoon et al. 2015; Wang et al. 2017). In essence, it appears that we are entering a new era of fire regimes with no historical analogue (i.e., “unknown unknowns”).

Following the notable success of their second warning (Altmetric Attention Score > 8500 at time of writing), the Alliance of World Scientists called for discipline-specific follow-up papers (e.g., Finlayson et al. 2018). This paper is an answer to that call for the topic of wildland fire. We touch on wildland fire issues of global importance but keep the main focus on Canada, a country that is facing major changes in fire regimes (i.e., variations in ecosystem fire patterns such as frequency, timing, size, and intensity) both currently and predicted over the remainder of the century. Importantly, several of the environmental issues raised in the second warning are relevant to anthropogenic impacts on fire regimes, which we discuss in the following section.

## 2. Wildland fire and the second warning

### 2.1. Climate change

Considerable research has been done on the potential effects of anthropogenic climate change on future wildfire regimes, both in Canada and globally (Table 1). In Canada and many areas of the world, wildfires are predicted to become more frequent and severe. The predicted impacts are variable, however, as some regions are expected to experience similar or decreased fire activity, which alludes to the complex interplay between fuels, weather, climate, and wildfire.

Perhaps the biggest impact on future fire regimes will be driven by climate-change effects on fire weather. Fire, weather (i.e., short-term changes in the atmosphere), and climate (i.e., long-term weather patterns in a specific region) are strongly linked, as temperature, wind, precipitation, and atmospheric moisture, among others, are crucial factors driving wildfire activity. While weather determines daily fire weather, climate may influence vegetation (fuels), as well as long-term trends in fire weather on interannual to decadal time scales. For instance, weather has a direct effect on fuel moisture (which may be the most important characteristic of fuels related to ignition potential), wind speed is a primary meteorological factor in individual fire growth, and temperature has often been suggested as the most important variable in accounting for overall annual wildfire activity (Flannigan et al. 2005, 2009a; Parisien et al. 2011). Climate change projections predict potentially extreme changes in the aforementioned weather variables across most of the world (e.g., higher temperatures, increased incidences of drought, and extreme wind events; IPCC 2014); therefore, future fire weather is expected to be influenced by the changing climate.

In Canada, the Canadian Forest Fire Weather Index System uses the Fire Weather Index (FWI) as a fire danger rating metric derived from surface temperature, precipitation, humidity, and wind speed measurements (Van Wagner 1987). The FWI is expected to increase in Canada, but with significant variation across the country (Bergeron and Flannigan 1995; Amiro et al. 2001; Wang et al. 2015). Likewise, increases in seasonal severity rating (SSR; a relative indicator of the fire season severity based on the FWI) is projected to increase across Canada and North America due to, for

example, lower relative humidity, higher temperatures, and modified precipitation patterns (Flannigan and Van Wagner 1991; Flannigan et al. 2000; Kochtubajda et al. 2006). Research suggests that anthropogenic climate change has already increased the likelihood of extreme fire risk in western Canada by 1.5 to 6 times during the current decade (Kirchmeier-Young et al. 2017).

Anthropogenic climate change is also anticipated to affect fire season length (Wotton and Flannigan 1993; Flannigan et al. 2013), with observed trends in keeping with predictions. Worldwide, fire season length increased across approximately 25% of the vegetated surface from 1979 to 2013 and decreased across approximately 11%, equating to a 19% increase in global mean fire season duration (Jolly et al. 2015). Likewise, fire season has increased over large areas of North America from 1979 to 2015, with fewer areas experiencing a decrease (Jain et al. 2017). In Canada, trend analysis (1959–2015) suggests that the fire season starts approximately one week earlier and ends one week later (Hanes et al. 2019).

The majority of studies examining area burned by wildfire suggest an overall increase with climate change; however, changes in burned area will be heterogeneous as some regions are also projected to experience decreased or unchanged fire activity. Importantly, climate is not the only factor influencing area burned, as fire management, topography, insect outbreaks, and fuel characteristics, among others, can also play a role. Nonetheless, projections of area burned based on weather–fire danger relationships suggest a 75%–120% increase in area burned in Canada by the end of this century based on Canadian and Hadley Centre climate models, respectively (Flannigan et al. 2005). Podur and Wotton (2010) predicted an eightfold increase in area burned in fire management zones of Ontario by the end of the century. Trends in observed area burned seem consistent with climate change projections for several regions (Hanes et al. 2019). There has been an upward trend of area burned in Canada due to increasing temperatures consistent with responses to anthropogenic greenhouse gas and sulfate aerosol emissions (Gillet et al. 2004). Coops et al. (2018) found an increasing trend in area burned across Canada. Kirchmeier-Young et al. (2019) suggest that 86%–91% of the area burned in BC during 2017 can be attributed to human-caused climate change.

Climate change is anticipated to affect other fire regime metrics similar to fire weather and area burned (Table 1). Spread days, for example, are predicted to increase by >50% in western Canada and by 200%–300% in eastern Canada under a high-CO<sub>2</sub> forcing scenario (Wang et al. 2017). Head fire intensity is anticipated to increase in the boreal regions of western Canada (de Groot et al. 2013). Meanwhile, trend analysis suggests that the number and size of large fires across Canada have increased (Hanes et al. 2019).

Weather is also a key factor in lightning occurrence, which is a major cause of wildfires in many regions of the world. Globally, climate change projections suggest that lightning will increase in many parts of the world, resulting in more fires and greater area burned (Price and Rind 1994; Romps et al. 2014). For instance, lightning is predicted to increase by approximately 50% over the 21st century in the contiguous USA (Romps et al. 2014). In Canada, lightning is already a major cause of wildfire in many areas (Blouin et al. 2016; Stocks et al. 2002; Wierzychowski et al. 2002), responsible for about 50% of large fires and 90% of area burned (Hanes et al. 2019). A study of the northern boreal forest found that the large amount of area burned in 2014 and 2015 coincided with a record amount of lightning strikes (Veraverbeke et al. 2017). In that study, lightning strikes were correlated with precipitation and temperature, both of which are projected to increase by mid-century.

Research related to synoptic weather patterns suggests that climate-induced warming in the Arctic is weakening the jet stream, leading to stationary patterns associated with extreme weather events (Mann et al. 2017) — one of the driving factors of the jet stream is the temperature difference between the Arctic

and mid-latitudes, and as this temperature gradient diminishes due to faster warming in the Arctic compared with lower latitudes (“Arctic amplification”), the jet stream weakens (Archer and Caldeira 2008; Screen and Simmonds 2013). In the future, the weakening jet stream in combination with less ice in the western Arctic may lead to conditions favorable for strengthening and anchoring the west coast upper ridge during the fire season (Francis and Vavrus 2012; Cvijanovic et al. 2017), leading to the potential for increased incidences of extreme fire weather in, for example, BC and Arctic ecosystems. In fact, the extremely destructive May 2016 wildland fire in Fort McMurray, Alberta (the Horse River fire), was associated with anomalous planetary wave dynamics that, in combination with a strong El Niño during the previous winter, led to extremely warm and dry conditions in that region (Petoukhov et al. 2018). The extreme spring fire weather over western Canada during that time was very likely due to anthropogenically caused warming, which favours the development of a persistent upper ridge (Tan et al. 2019). There remains uncertainty, however, around the influence and mechanism of Arctic amplification on mid-latitude weather patterns, which is an ongoing field of research (Cohen et al. 2014; Overland et al. 2015; Vavrus 2018).

Another important aspect to consider is that increased biomass burning due to climate change and the associated potential increase in carbon (and other compounds) released into the atmosphere may itself have significant feedback effects on the carbon cycle and climate system (Harrison et al. 2018). Drawing from an international example, it was estimated that emissions from the Indonesian fires of 1997 were equivalent to 13%–40% of the annual global carbon emissions from fossil fuel use (Page et al. 2002). In Canada, estimates of wildfire emissions over the 1959 to 1999 period were equivalent to 18% of the carbon dioxide emissions from the Canadian energy sector (Amiro et al. 2001). Moreover, future emissions from Canadian fires are estimated to double in a 3 × CO<sub>2</sub> climate change scenario relative to a 1 × CO<sub>2</sub> scenario (Amiro et al. 2009). As well as the direct increase in atmospheric concentrations of greenhouse gases (and therefore radiative forcing), wildfire emissions can additionally lead to increased atmospheric aerosol levels or black carbon deposition on arctic ice and glaciers, the latter of which may lead to a warming effect due to reduced albedo (Ramanathan and Carmichael 2008). However, while there is clearly a need to include wildfire emissions in the global carbon cycle accounting (Sommers et al. 2014), a word of caution is required here due to the complex interplay among processes coupling the atmospheric and terrestrial systems. Indeed, the long-term healthy functioning of boreal forest ecosystems rely on disturbance mechanisms such as wildfire, and the cycling and uptake of carbon over long time scales should also be taken into consideration. Moreover, at local scales, individual fires can lead to other changes in the surface energy budget. In the boreal biome, these changes correspond to either warming or drying due to increased evapotranspiration for burned vegetation or cooling due to increased albedo when effects are integrated over longer time scales (Randerson et al. 2006; Liu et al. 2019). More work is therefore required to fully understand the effects of wildfire on the global carbon cycle and climate change effects.

## 2.2. Human population growth

Human population density can have an important influence on global fire activity. The combined impacts of a growing world population and climate change on future fire regimes are still debated, in large part because the diversity of socioeconomic contexts and ecosystem responses to fire can make the relationships between wildfire and human population density complex and nonlinear (Andela et al. 2017; Bistinas et al. 2013). This complexity arises from the influence of several factors such as anthropogenic ignitions, surface fuel production, fuel fragmentation, and cultural behaviour (Guyette et al. 2002). In North America, the gen-

eral relationship between human population density and burned area appears to be non-monotonic, where burned area increases with population density up to a certain threshold and then decreases once that threshold has been crossed (Bistinas et al. 2013). One study suggests that population growth in the future could result in either an increase or decrease in global wildfire emissions under certain climate change scenarios dependent upon the rate of urbanization, where urbanization is positively associated with increased emissions (Knorr et al. 2016). In Canada, a higher human population under warming climate conditions may very likely result in increased wildfire activity on the landscape given that people are a primary cause of fires (see below), while climate-driven changes in vegetation, fire weather, and fuel moisture may create conditions more conducive to fire ignitions while creating more difficulty in suppression (Flannigan et al. 2009a; Podur and Wotton 2010).

Human-caused fires influence fire regimes in many ways, including alterations to spatial patterns of ignitions, fire season lengths, available fuels, and land use (Bowman et al. 2009, 2011). People are also the major cause of fires in many regions of the world; for example, >90% of European wildfires and 84% of wildfires in the contiguous USA have been attributed to human cause (Ganteaume et al. 2013; Balch et al. 2017). In the contiguous USA, for instance, the human-caused fire season was found to be three times longer than the lightning-caused fire season, resulting in an additional 40 000 wildfires per year, on average, and 44% of area burned (Balch et al. 2017). In contrast, large human-caused fires in Canada account for ~50% of wildfires and are responsible for ~10% of total area burned (Hanes et al. 2019). Human-caused fires appear to have declined in Canada since 1980 (Hanes et al. 2019); however, such fires are still a concern, as they are generally most prominent during the shoulder seasons in which fuels are especially flammable. As such, human-caused fires have likely been contributing to lengthening the Canadian fire season (Hanes et al. 2019). Human-caused fires may also tend to occur closer to communities.

Another important consideration is that more Canadians live and work in the forest than ever before. In 2017, >317 000 people were employed in the forest industry (Natural Resources Canada 2019a), and approximately 3.9 million lived in the boreal region in 2016 (Natural Resources Canada 2019b). Development is increasing in many parts of the country, including future envisioned expansion into the northern regions (Canadian Northern Development Strategy 2019), currently illustrated by Ontario's "Ring of Fire" industrial development. Yet, development in fire-prone areas has already exposed many communities to extremely destructive wildfire events (e.g., Kelowna 2003, Slave Lake 2011, Fort McMurray 2016). The Horse River wildfire, for example, was the costliest disaster in Canadian history, with insured property damage estimated at CAN\$3.58 billion (Insurance Bureau of Canada 2016), with approximately 590 000 ha burned, 2400 private dwellings destroyed (Statistics Canada 2019), and 90 000 residents evacuated. In the future, it does not seem unreasonable to speculate that longer fire seasons and more fire-conducive weather conditions, in combination with more people and associated activities in forested areas, will very likely result in more human-caused fires, more community and infrastructure exposure to wildfires, and an increased probability of disaster, all of which could have severe economic impacts. Such impacts could be especially prominent in the future if an increase in population density is concomitant with an increase in human demand for natural resources and ecosystem services affected by more active wildfire regimes.

### 2.3. Biodiversity and forests

Many of the potential impacts of fire regimes on biodiversity and forests lie in the realm of fire ecology, a branch of wildfire research that focusses on the relationships between wildland fire and the affected environment. Wildfire itself is an important eco-

logical process that helps shape and maintain many ecosystems (Bond et al. 2005; Pausas and Keeley 2009). Flames promote vegetation regeneration and adaptation, create ecosystem heterogeneity and resilience, and play an important role in soil nutrient dynamics, among many other ecological effects (Lavorel et al. 2007; Archibald et al. 2017). The paramount role that fire has in the healthy functioning of such ecosystems helps maintain the services that they provide over the long term such as biodiverse and productive landscapes, carbon cycling, and clean water supplies (Adams 2013). This is particularly true of the Canadian boreal forest in which many plant species have evolutionarily adapted to fire (Rowe and Scotter 1973).

Canadians, however, will likely face alterations to forests, vegetation, and biodiversity distributions in the future due to climate change and wildfire dynamics. Anticipated increases in fire frequency and severity are predicted to accelerate vegetation shifts and thus conversion to different fire regimes by the end of the century (Whitman et al. 2018). For instance, a simulation of climate-induced vegetation change that also incorporated future wildfire regime scenarios found that even under conservative assumptions, wildfire could speed the transition of approximately half of the mixedwood and conifer forests in Alberta to deciduous woodland and grassland over the next century (Stralberg et al. 2018). Such landscape alterations will come with requisite changes in forest ecosystem services provided to Canadians such as timber and other forest products, carbon storage, and water supply.

Significant changes in the distribution of vegetation brought about by wildfire – climate change interactions would thus affect the distribution and biodiversity of wildlife species (McKenzie et al. 2004). In the future, areas with greater fire activity may see an increase in species that benefit from wildfire (assuming that ecosystem carrying capacity is not hindered by excessive land degradation and desertification), as many species of insects, birds, and mammals in Canada benefit from postwildfire habitat (Nappi et al. 2004). However, increases in future wildfire activity may severely impact negatively affected species. One such species is the boreal woodland caribou (*Rangifer tarandus caribou* (Gmelin, 1788)), which faces consequential loss of habitat in Alberta under future climate change and wildfire regimes (Barber et al. 2018). Furthermore, the synergistic effects of climate change and wildfire are expected to favour invasive species and reduce fire refugia, further altering current patterns of plant and animal biodiversity (McKenzie et al. 2004).

Climate change impacts on forest ecosystems can be considered environmental stressors and may predispose vegetation to secondary stressors such as insect and disease attacks and increased susceptibility to drought (Weber and Flannigan 1997). There has been widespread concern that climate-driven insect outbreaks such as mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins, 1902) may result in an increase in the frequency, extent, and severity of wildfires in North America. Research has shown major alterations to the characteristics (e.g., reduced foliar moisture content, altered chemistry, and increased flammability) and arrangement of forest fuels following MPB outbreaks (Jolly et al. 2012; Page et al. 2012, 2014). Drier conditions, combined with greater fuel loads from insect-affected trees, may temporarily increase fire intensity and hazard after ignition (Weber and Flannigan 1997). Thus, projected future increases in extreme fire weather may interact with insect-affected stands, resulting in more severe fires. Research on this topic has yielded mixed results. While some studies have found increases in fire extent and severity following MPB outbreaks (Turner et al. 1999; Schoennagel et al. 2012; Harvey et al. 2014; Page et al. 2014; Nelson et al. 2016), others have not found a link between MPB events and wildland fire extent (Mietkiewicz and Kulakowski 2016; Hart et al. 2015). The inconsistencies among studies may reflect the influence of local and regional factors (e.g., climate, topography, forest composition, drought) that overshadow the influence of MPB out-

breaks (Kulakowski and Veblen 2007; Nelson et al. 2016), as well as differing methodological approaches. However, a study documenting fire behaviour in both experimental and wildland fires in BC found that rates of spread were two to three times greater in MPB-affected stands than predicted for unaffected lodgepole pine (*Pinus contorta* Douglas ex Loudon) stands, while crowning occurred under lower fire danger conditions (Perrakis et al. 2014). The results of the aforementioned study supported anecdotal observations (i.e., greater rate of spread and intensity) by provincial fire suppression crews and behaviour analysts. Ongoing research is needed to better elucidate what impacts the combination of climate change, MPB, and other insect outbreaks may have under future fire regimes.

#### 2.4. Water security

There is a growing understanding of the role of fire in surface hydrology and the functioning of aquatic ecosystems (Allen et al. 2003; Bladon et al. 2008; Musetta-Lambert et al. 2017). Earth-system simulations have shown that wildfires play an important role in the global hydrologic cycle and, consequently, on the movement of water resources on land and the availability of surface freshwater (Li and Lawrence 2017); however, medium-term impacts (~10 years) on the functioning of watersheds commonly lead water managers in Canada, and elsewhere, to consider wildfire as a major threat to water security (Martin 2016; Robinne et al. 2018). For example, there have been mounting concerns regarding the potential short-term threats that wildfire presents to potable water supplies, as water contamination by excess nutrients, sediments, heavy metals, and organic matter from burned areas can strain drinking-water treatment processes, with a growing potential for treatment failure (Emelko et al. 2011). Concerns are also arising regarding how best to provide protection against destructive postfire flash floods and debris flows (Jordan 2016). In the longer term, greater fire activity and hydrologic extremes (e.g., droughts, storms, floods) may threaten the capacity of forested watersheds to provide adequate quantities of good-quality freshwater to downstream communities and ecosystems in some areas (Bladon et al. 2014).

### 3. Health

In addition to the ecological concerns outlined by world scientists, the circumstances unique to wildfire can also have serious effects on human health, including respiratory, cardiovascular, ophthalmic, and psychiatric problems (Bowman and Johnston 2005; Finlay et al. 2012). Perhaps most prominent among the negative health effects of wildfire are those associated with wildfire smoke (Reisen et al. 2015; Black et al. 2017). Such concerns are warranted, as there are, on average, an estimated 339 000 smoke-related human deaths per year globally (Johnston et al. 2012). Research on the health effects of wildfire smoke suggest that some demographics are more susceptible to its negative effects, including pregnant women, children and infants, the elderly, those of low socioeconomic status, those suffering from cardiovascular or respiratory disease, and those who experience the greatest exposure, e.g., wildland firefighters (Liu et al. 2015; Reid et al. 2016; Black et al. 2017). In Canada, public health impacts related to wildfire smoke have been increasingly documented following recent large fires (e.g., Dodd et al. 2018; Landis et al. 2018). Moreover, rural and remote Indigenous communities in Canada are frequently at high risk from wildfire and may be more severely affected than the general population (Christianson 2015).

Furthermore, wildfire smoke may be changing how society views wildland fire, as urban centres have been increasingly impacted by poor air quality. Traditionally, wildfire has been considered primarily a rural problem; however, smoke from wildfires can be transported across long distances (Lutsch et al. 2018) to impact major urban centres, as was evident in cities across North America during the summer of 2018. Unfortunately, climate

change projections suggest that toxic smoke emissions from wildfires will increase in North America by mid-century (Spracklen et al. 2009), thus it is likely that health problems related to wildfire smoke will get worse over the course of the century.

Another growing area of concern related to wildfire and human well-being pertains to mental health. Significant mental health problems associated with wildfire disasters have been documented. For example, a study of Fort McMurray residents following the Horse River fire showed increased incidences of anxiety, depression, and suicidal thoughts (Cherry and Haynes 2017; Brown et al. 2019). With predicted increases in future fire activity and a growing population, we may very well expect that public health problems, health care costs, health expenditures, and mortalities associated with wildfire may rise in the future.

### 4. Fire management

Current wildfire management policies predominantly focus on exclusion, given wildfire's potential impact on public health and safety, property, and timber supplies (Hirsch et al. 2001). However, past efforts to exclude wildfire have in some ecosystems resulted in increased fuel loads and alterations to forest composition and structure, which in turn leads to more extreme fire behaviour should fire occur. Furthermore, the legacy of fire exclusion practices is anticipated to interact with climate change, insect outbreaks, and other anthropogenic influences on forests to further influence fire regime changes. Ongoing climate change is already exacerbating existing challenges to fire management and suppression in Canada, while traditional approaches to fire suppression might be reaching their limit of economic and physical effectiveness (Podur and Wotton 2010). This is cause for concern, given that future changes in fire regimes are likely to lead to increases in fire occurrence, intensity (e.g., crown fires), fuel consumption, area burned, and fire season length in many forested ecosystems across the country. In fact, studies investigating the future of fire suppression in Canada suggest that fire management agencies will be severely challenged over the current century (Flannigan et al. 2009b). For example, a fire growth and suppression simulation model found that the number of escaped fires (where an escape is defined as a fire > 4 ha in size) in Ontario could increase by 92% by the end of this century under changing climate conditions (Podur and Wotton 2010). It has also been estimated that the number of days that fire intensity exceeds suppression capabilities will increase substantially over the remainder of the century (Wotton et al. 2017). The economic costs of wildfire suppression are also likely to rise in the future with increased fire activity; wildfire management agencies in Canada already spend, on average, \$800 million per annum towards fire management (Stocks and Martell 2016). Such expenditures have been rising due to increasing fire occurrences and extreme fire weather in recent years and are projected to increase (Stocks and Martell 2016). Furthermore, there are significant financial costs associated with health and safety evacuations and losses due to wildfire, which may also increase over the next century.

### 5. Looking to the future

New perspectives on wildfire suppression have been developing in recognition of the growing challenges associated with wildfire management, including the negative effects of historic wildfire exclusion practices. In light of these concerns and growing recognition of the importance of allowing wildfire in many ecosystems, there has been an increasing emphasis on managing wildfire suppression to capture the beneficial aspects of fire. A primary shift in the philosophy of wildfire management has been towards an "appropriate response" in which managers strive to minimize the economic and social impacts of wildfire while simultaneously maximizing its ecological benefits (Hirsch et al. 2001). Thus, the appropriate response strategy is one in which wildfire is allowed

on the landscape to promote ecosystem health and resiliency when human safety and property are not at risk. Such an approach is also beneficial in recognition that traditional fire suppression may be nearing its limit of effectiveness. Yet, allowing wildfires to burn naturally to support ecosystem functioning becomes increasingly difficult as values at risk increase in fire-prone areas. In fact, it has been suggested that institutional conservatism (i.e., risk adversity) within Canadian wildfire management agencies hinders allowing more fire back on the landscape due to the perceived risks involved and stakeholder pressures to exclude fire (Sherry et al. 2019). There is also a need for more data on the components of risk so that fire management agencies can base their priorities on robust and contemporary information such as where values (e.g., communities, industry, water, ecosystems, and species at risk) are located and how vulnerable they are (e.g., demographics, ease of evacuation, rarity). Thus, implementation of an appropriate response framework will necessitate increased engagement with stakeholders to identify values at risk on the landscape.

In Canada, wildfire management adheres to five emergency management phases: prevention, mitigation, preparedness, response, and recovery. Currently, most effort and resources are spent on response; however, given what is foreseen for the future, we suggest that more effort should be spent on the prevention, mitigation, and preparedness phases (that being said, we expect response to remain a critical management phase given the projected increases in fire activity, likely with expanding effort and expenditures). For example, increasing fire management planning at the landscape level such as fuel management (e.g., thinning) and prescribed burns to proactively protect communities at risk, as well as developing harvesting and silvicultural regimes to reduce wildfire hazards. Because we expect to live with increased fire activity in many areas, it makes sense to make high-value areas (e.g., communities) more fire resistant and resilient. In Canada, the FireSmart program has been developed for this purpose to provide citizens with information related to fuel management, planning, education, cooperation, training, and development (FireSmart Canada 2019). In fact, it may be essential that increased responsibility and participation be placed on individuals, communities, and other stakeholders in preventing destructive wildfires (Sherry et al. 2019) in the face of increased wildfire activity, the anticipated challenges facing wildlife suppression agencies, and the importance of maintaining the decreasing trend of human-caused fires. Such an approach would require urban developers, ecosystem managers, and fire researchers to explore landscape management options, particularly fuel management, in concert with harvesting, grazing, fireproofing, and carbon management. Furthermore, development may have to be restricted or forbidden in certain areas. To that end, investment in social sciences to better understand stakeholder attitudes and better educate and interact with residents, including Indigenous communities, would be beneficial in developing a more holistic approach to wildfire management (Sherry et al. 2019).

Given the anticipated challenges and unknowns associated with the future of wildfire in Canada and around the world, there is a significant need for investment in wildfire research and development to face the obstacles that future wildfire regimes will place on society. Advancements in science and technology are leading to novel and cutting-edge approaches to studying wildland fire. For example, there has been an increased use of machine learning and artificial intelligence (ML-AI) techniques in wildfire science covering a range of topics. Examples include extreme fire weather prediction (Lagerquist et al. 2017), ensemble lightning prediction modelling (Blouin et al. 2016), and automated burn scar mapping (Cao et al. 2009). Other advancements in fire science worth mentioning include improved numerical weather and fire growth models. In the future, ML-AI methods could be applied to aid in operational resource planning (e.g., locations of bases, po-

sitioning number and type of resources, deployment of specific resources) and in the development of automated early warning systems. Additional examples (non-exhaustive) of future research to facilitate managing the challenges of future wildfire regimes in Canada include the following:

- improved classification and monitoring of fuels (e.g., fuel mapping and moisture through remote sensing);
- improved decision support systems (to reduce subjectivity, e.g., risk assessment tools);
- improved fire detection (e.g., through remote sensing);
- improved medium- and long-term (e.g., seasonal) forecasting (to aid in strategic and long-range planning of firefighting resources);
- creating tools and protocols for postfire restoration;
- future landscape change simulations (to prepare for future possibilities);
- update and enhance the Canadian Forest Fire Danger Rating System;
- update the Fire Occurrence Prediction (FOP) system (e.g., include lightning forecasts);
- improved understanding of the relationships between wildfire and hydrological functioning; and
- develop a set of standardized guidelines for addressing fire risks to water security.

Importantly, such increased research investment would have to be concomitant with an increase in the number of highly trained personnel required to collect, analyze, and interpret such data and disseminate the results. We note, however, that while important, these suggestions will primarily aid in managing the anticipated future increases in wildfires due to climate change and other anthropogenic activities and are not “solutions” per se. In keeping with the world scientists’ second warning, the ultimate solution to mitigating or eliminating the potential for more active wildfire regimes due to anthropogenic activity is by changing society’s current way of doing business, perhaps most effectively by reducing fossil fuel emissions and other climate change exacerbating activities.

## 6. Conclusion

The world scientists’ second warning provides the opportunity for wildland fire researchers to raise the profile of the potential impacts that human activities may have on future fire regimes and what impacts such future fire regimes might have on humans. The second warning itself argues that humanity must practice a more environmentally sustainable way of living to prevent or minimize the catastrophic impacts that our activities have on the environment and ultimately ourselves. This philosophy holds true in the domain of wildland fire, where a multitude of human impacts interact to produce more extreme wildfire activity, with detrimental effects on individuals and society. For the predicted near future, more active fire regimes, fire suppression limitations, and the need to balance both the positive and negative aspects of wildfire necessitate that people adapt and learn to live with more fires on a rapidly changing landscape (e.g., Moritz et al. 2014). Changes in wildfire regimes may be considered early indicators of the negative effects that our current way of doing business is having on our natural world, with tangible effects on people’s day to day lives. As such, fire regime changes in the near future may work to speed the impetus for individuals, corporations, and governments to transition to a more environmentally sustainable future, before it is too late.

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