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Impacts of climate change on fire activity and fire management in the circumboreal forest

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Abstract

Forest fires are a significant and natural element of the circumboreal forest. Fire activity is strongly linked to weather, and increased fire activity due to climate change is anticipated or arguably has already occurred. Recent studies suggest a doubling of area burned along with a 50% increase in fire occurrence in parts of the circumboreal by the end of this century. Fire management agencies' ability to cope with these increases in fire activity is limited, as these organizations operate with a narrow margin between success and failure; a disproportionate number of fires may escape initial attack under a warmer climate, resulting in an increase in area burned that will be much greater than the corresponding increase in fire weather severity. There may be only a decade or two before increased fire activity means fire management agencies cannot maintain their current levels of effectiveness.

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Fire in the circumboreal

Fire is the major stand-renewing agent for much of the circumboreal forest zone, greatly influencing forest structure and function. Current estimates are that an average of 10–15 million hectares burn annually in boreal forests, primarily in Siberia, Canada, and Alaska (Fig. 1, Table 1; also see Stocks *et al*., 2002), and there is a growing global awareness of the importance and vulnerability of this region with respect to future climate change. Fire activity is strongly influenced by four factors – weather/climate, fuels, ignition agents, and human activities (Johnson, 1992; Swetnam, 1993). Recently, our climate has been warming as a result of increases in radiatively active gases (carbon dioxide, methane, etc.) in the atmosphere caused by human activities (IPCC, 2007). Such warming is likely to have a rapid and profound impact on fire activity in the circumboreal forest zone (Weber & Flannigan, 1997; Soja *et al*., 2006). Gillett *et al*. (2004) use a coupled climate model to show that the observed increases in area burned in Canada during the last four decades is the result of human-induced climate change. Additionally, it appears that temperature is the most important predictor of area burned in Canada and Alaska, with warmer temperatures associated with increased area burned (Duffy *et al*., 2005; Flannigan *et al*., 2005).

The objective of this paper is to review and synthesize the impacts of climate change on fire activity and particularly on fire management in the circumboreal forest zone. The relationship between fire and climate change could have significant implications for forests, forestry activities, community protection, and carbon budgets. On an average, fire management agencies in Canada alone spend 500 million dollars a year on direct suppression costs; if fire activity increases, these suppression costs would likely rise dramatically. Additionally, fire management agencies operate with a narrow margin between success and failure; a disproportionate number of fires may escape initial attack under a warmer climate, resulting in an increase in area burned that will be much greater than the corresponding increase in fire weather severity (Stocks, 1993). Fire management in the circumboreal may be reaching a tipping point within the next decade or two.

Contemporary fire activity

Expansion of human settlement into the boreal zone was largely driven by a growing economic need for the wealth of natural resources in this region, including

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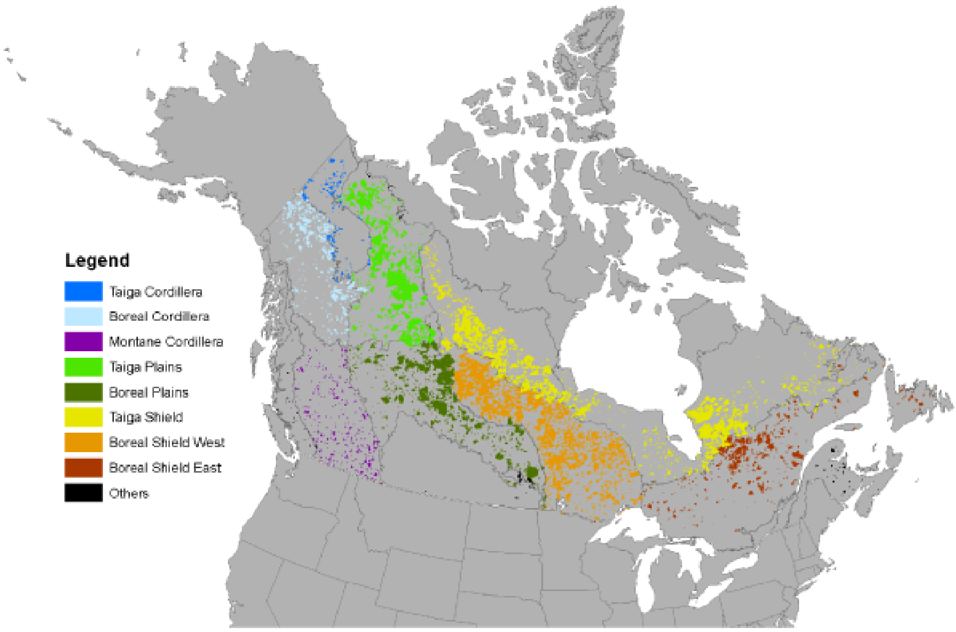

Fig. 1 Large fires for Canada 1980–1999. Large fires were defined as greater than 200 ha. The fire polygons were kindly provided by Canadian fire agencies (provinces, territories, national parks).

Table 1 Cumulative area burned, forested area, and percent area burned for ecozones in Canada (1980–1999) as shown in Fig. 1

Ecozone	Area burned ($\times 10^6$ ha)	Forested area ($\times 10^6$ ha)	% area burned
Taiga Plains	11.237	51.924	21.64
Taiga Shield	12.601	110.072	11.45
Boreal Shield West	15.423	67.116	22.97
Boreal Shield East	3.076	92.859	3.31
Boreal Plains	7.921	59.277	13.36
Taiga Cordillera	0.438	11.729	3.74
Boreal Cordillera	2.970	27.692	10.73
Montane Cordillera	0.271	41.079	0.66

forest products. In the late 1800s and early 1900s, there were a number of disastrous fire seasons, in which large, uncontrolled wildfires associated with natural resource exploitation frequently burned over small communities, killing large numbers of citizens (Pyne, 2007). This led to a recognized need for organized fire protection, which in turn has led to the development, over the past century, of highly efficient forest fire management systems designed to detect and suppress unwanted fires quickly. However, fire is a natural, ecologically desirable, and essential stand-renewing agent in circumboreal forests. After a period of attempted fire exclusion revealed this as an economically and physically impossible goal, fire management agencies now strive to balance the need to protect life, property, and industrial/recreational interests, with the ecological need for landscape-scale fires. This has been addressed through fire management strategies that prioritize the protection of high-value areas while permitting natural fire in the more remote northern regions common to Canada and Russia, while in Alaska, fire is allowed to burn naturally over most of the landscape. Fires in these remote areas are monitored, but usually only occasionally actioned if values are threatened.

Despite the presence of highly sophisticated fire management programs that have had an influence on their extent and impact, large boreal fires continue to dominate the forested landscapes of circumboreal countries. Multiple ignitions (usually from lightning), in combination with the periods of extreme fire weather common to continental climates, frequently result in numerous outbreaks of the very large, high-intensity wildfires that are responsible for the existence of the boreal forest. In general, fire management agencies control close to 97% of all fires before they reach 200 ha in size, but the remaining 3% grow larger and account for almost 97% of the area burned (Stocks *et al.*, 2002).

Annual Canadian and Alaskan fire statistics have been archived since the early 1920s and 1940s, respectively, but are only considered to be comprehensive since the advent of satellite coverage in the early 1970s. Before this period, large, sparsely populated regions of Canada and Alaska were not monitored on a regular basis, so statistics increasingly underestimate area burned as one moves back in time from the early 1970s, making a longer term trend analysis impossible. However, since 1970, statistics can be considered reasonably complete over all of Canada and Alaska. Over the past three to four decades, Canadian fires have burned over an annual average of 2 million hectares, with $\sim$50% of this area burned occurring in largely unprotected northern regions. Interannual variation in area burned is quite high, varying by more than an order of magnitude (from less than 0.5 million hectares in low years to more than 7.5 million hectares in extreme years). Several papers have found that there is a significant increasing trend in area burned in Canada and Alaska in the 30 years or so (Podur *et al*., 2002; Gillett *et al*., 2004; Kasischke & Turetsky, 2006).

Official Russian fire statistics from the late 1940s through 1992 were summarized by Korovin (1996) and showed a range between 0.2 and 2.7 million hectares burning annually. However, these were official Russian government statistics, which have been shown in recent years to have been gross underestimations of actual fire activity (Stocks, 1991; Dixon & Krankina, 1993; Cahoon *et al*., 1994; Rylkov, 1996). Meaningful statistics on Russian fire activity have been available since the establishment of a NOAA-AVHRR downlink in the Siberian city of Krasnoyarsk in 1995. Over the past decade, this satellite data has been used to show conclusively that much larger areas burn annually in Russia than had been previously reported. Satellite data gathered by the Remote Sensing Laboratory at the Sukachev Institute of Forest in Krasnoyark shows an annual average of 9.3 million hectares burning in Russia during the 1996–2005 period (Goldammer, 2006), with large interannual variation (range 4.5–17.4 million hectares). These estimations are in line with other recent studies (Kasischke *et al*., 2005; Soja *et al*., 2006). At the present time, an investigation is underway using NOAA-AVHRR imagery to map large fires in Russia during the 1980–1994 period. When completed, a 25-year record of fire activity in Russia will be available, which will provide a credible database from which projections of future fire activity, emissions, etc. can be developed.

Fire and carbon cycling in uplands

Boreal regions store about 30% of the world's soil carbon pool, due primarily to slow rates of decomposition under cold, wet climates. Fire plays a major role in carbon storage and emissions in northern regions, because it is the major stand-renewing agent throughout most of the boreal forest. The magnitude of the effect of fire on net biome productivity depends on three main processes. First, carbon is lost through direct combustion. Most of this is in the form of carbon dioxide, but quantities of carbon monoxide, methane, long-chain hydrocarbons, and carbon particulate matter are also emitted. Other greenhouse gases and elements (such as nitrogen compounds) are also released. Amiro *et al*. (2001) determined that Canadian forest fires released an average of $27\,\mathrm{Tg\,C\,yr^{-1}}$, but in some years, this exceeded $100\,\mathrm{Tg\,C}$, which is about the same amount of carbon as that is released by fossil fuel emissions in Canada. The same climate controls that contribute to soil C sequestration in boreal regions also promote mercury storage in soils, yet terrestrial mercury stocks are extremely vulnerable to volatilization during fire. Turetsky *et al*. (2006) estimated that western Canadian forest and peat fires released an average of about 23 tons of mercury to the atmosphere; during large fire years, these emissions approached industrial mercury emissions across all of North America. Given that the majority of fire-related mercury emissions undergo long-range transport, likely to polar regions, the response of fire regimes to changing climate could have important consequences for the health of northern food chains.

The second process is decomposition of fire-killed vegetation. In severe fires, much of the finer vegetative materials, small twigs, and the top of the duff layer are consumed by the fire, leaving coarser materials behind. These materials decompose at a rate that depends on environmental factors, microbial populations, and the quality of the substrate for decomposition. The physical characteristics also change with the charred surface, causing a decreased summer albedo. However, the surface energy balance effect quickly changes as successional vegetation develops, which increases albedo and changes partitioning between latent and sensible heat flux (Chambers & Chapin, 2002). The third process is the dynamics of vegetation following the fire. Boreal vegetation has adapted to fire, and there are a host of species that thrive in the postfire environment. The vegetation is a photosynthetic sink for carbon. The net ecosystem production (NEP) following fire is a combination of heterotrophic respiration (i.e., decomposition) and autotrophic fixation. Current research is underway measuring NEP at sites following fire in boreal forests of North America (Litvak *et al*., 2003; Amiro *et al*., 2006). This research has shown that forests are carbon sources soon after fire, becoming carbon sinks in the following decades. The magnitude of the flux depends on the successional nature of the forest and environmental factors, and research projects are investigating the interaction of processes to understand and model the net effects to the forest carbon balance.

Fire and carbon cycling in peatland and permafrost ecosystems

While considerable attention has been paid to the effects of fire activity on the structure and function of boreal forests, less is known about the vulnerability of boreal peatlands to burning. Peat accumulates due to an imbalance between plant C inputs and soil C losses such as organic matter decomposition. Globally, peatlands cover only 2–3% of the land surface ($4 \times 10^6\,km^2$; Joosten & Clarke, 2002), but store an estimated 30% of the world's soil C pool (Gorham, 1991).

Peatland ecosystems occur mainly in boreal regions, covering 25–30% of the boreal forest region globally (Gorham, 1991; Wieder *et al.*, 2006). Estimates of the total northern peatland C pool have ranged from 42 to 489 Pg (reviewed by Vasander & Kettunen, 2006), although Turunen *et al.* (2002) suggest that boreal peatlands globally store between 270 and 370 Pg, a substantial proportion of the estimated total boreal forest C stock of 471 Pg (IPCC, 2000). Generally, warmer temperatures will increase evapotranspiration in peatlands, lowering water table position (Roulet *et al.*, 1992) and decreasing surface soil moisture content. While surface peat moisture content is expected to influence fire behavior directly (Zoltai *et al.*, 1998), afforestation or other vegetation changes in response to drier peatland conditions (Minkkinen & Laine, 1998) could have indirect influence on fire activity in these ecosystems by altering fuel loading and connectivity.

Peatlands actually represent a diversity of ecosystem types that vary considerably in hydrology and vegetation structure, from forested, ombrotrophic bogs to graminoid-dominated, saturated, or near-saturated minerotrophic fens. Because of varying moisture conditions and fuel structure, these different peatland types also will vary in fire return intervals and rates of fuel consumption. Fire return intervals typically range from 50 to 500 years in boreal forests (Zackrisson, 1977; Laberge & Payette, 1995), and from 80 to 1100 years in temperate and boreal peatlands (Heinselman, 1973; Tolonen, 1985; Kuhry, 1994). Fire frequency in peatlands typically is investigated using paleoreconstructions of charcoal in peat cores. However, it is possible that the use of charcoal reconstructions underestimates fire frequency in at least some peatland types due to charcoal degradation or migration in the peat column and/or the large spatial heterogeneity in fuel consumption that tends to characterize peat fires. Using fire perimeter maps and detailed land cover maps of forests and wetlands, Turetsky *et al.* (2004) estimated fire return intervals of 123 and 105 years for bogs and fens, respectively, in central Alberta. These relatively short fire return intervals are not surprising, given that peatlands of western Canada exist on the dry climatic edge of peatland distributions. Nonetheless, peatlands in continental boreal regions such as Alberta store tremendous reservoirs of soil C and are likely to become increasingly vulnerable to fire, as climate change lowers water tables and exposes C-rich peat to burning.

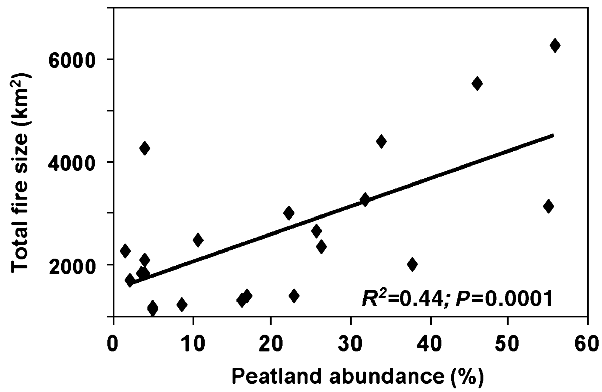

Fig. 2 Relationship between peatland abundance on the landscape and the size of large fire events. There was a spatial threshold of $1500\,km^2$, above which there was a positive relationship between fire size and peatland abundance. There was no significant relationship between peatland abundance and the size of smaller fire events, suggesting that peatland distributions are important only to larger fire events that likely occur during extreme fire weather conditions. Figure adapted from Turetsky *et al.* (2004).

The frequency of large fire events ($>1000\,km^2$) has increased across boreal North America from the 1960s to the 1990s, and fires are occurring later in the growing season (Kasischke & Turetsky, 2006). We believe that these fire regime changes make many peatlands more vulnerable to deep soil consumption, as burning is more likely to occur during the period of maximum water table drawdown and fuel exposure. The amount of peatlands on the landscape of western Canada is positively related to the size of large fire events, but not small fires (Fig. 2). Given that annual areas of peatland burned in this region are correlated with fire weather variables such as the drought moisture code (Turetsky *et al.*, 2004, 2006), we suggest that fuel loading in peatlands, particularly under the extreme fire weather conditions that lead to the development of large fire events, is important to fire behavior in at least some boreal ecoregions.

Published estimates of fuel consumption during peat fires are rare, but average $3.2\,kg\,C\,m^{-2}$ during individual fire events (reviewed in Turetsky & Wieder, 2001). Generally, however, consumption rates show

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tremendous spatial variability in peatlands due to microtopography controls on soil moisture (Benscoter & Wieder, 2003) and fire weather conditions. Using these average fuel emission estimates, Turetsky *et al.* (2004) suggest that peat fires across western Canada (AB, MB, SK, NWT) emit up to 6 Tg C to the atmosphere annually. Given that fires release $27 \pm 6\,\mathrm{Tg\,C\,yr^{-1}}$ Canada-wide, peat fires already appear to be important contributors to regional C emissions. However, given that C density increases exponentially with depth throughout peat columns, deeper burning invoked by drought and lower water table position in peatlands has the potential to greatly exacerbate atmospheric C emissions. It is important to note that, unlike fuel consumption during upland forest fires, consumption during peat fires is always moisture-limited rather than fuel-limited. Thus, increases in fuel consumption and C emissions under climate change are likely to be greater in peatlands than in uplands.

Severe fire activity in peatlands results in the combustion of deep peat layers and can last for several months, sometimes overwintering underneath snowpacks. Even in continental regions, consumption during peat fires likely is dominated by smoldering rather than active flaming. Thus, fires that affect large areas of peatlands are likely to have different trace gas emissions than more upland-dominated fires. Increasing wildfire activity in boreal peatlands will lead to new concerns for fire-related emissions; byproducts such as CO, CH_4, CH_3Br, CH_3Cl (Manö & Andreae, 1994) and Hg (Turetsky *et al.*, 2006) will become more significant, as peat experiences increasing smoldering consumption. Much of the boreal forest region is affected by discontinuous permafrost, where permafrost is found most commonly in peatlands due to the thermal insulating qualities of peat (Zoltai & Tarnocai, 1975). In western Canada, about 30% of the peatlands are underlain by permafrost (Vitt *et al.*, 2000), occuring mainly as palsas or peat plateau landforms (Brown, 1980; Seppälä, 1988; Harris, 1998). These permafrost landforms have drier soil moisture contents than adjacent unfrozen peatlands due to the volume expansion of frozen soil water, and can be characterized with relatively dense tree canopies. Robinson & Moore (2000) concluded that rates of peat accumulation in permafrost peatlands were low mainly due to high fire frequencies and losses of soil C due to burning. Turetsky & Wieder (2001) measured greater rates of organic matter consumption in permafrost landforms relative to nearby forested bogs with no permafrost. Thus, permafrost aggradation can increase the vulnerability of peatlands and other poorly drained ecosystems to burning. Conversely, the presence of permafrost on slopes or in uplands impedes soil drainage conditions and increases the moisture content of surface soils. In these situations, the presence of permafrost is more likely to dampen fire activity.

Fire activity plays an important role in permafrost dynamics. Fires remove surface organic matter and alter insolation, increase soil temperatures, and ultimately lead to thicker active layers. The effects of permafrost thaw on drainage conditions depend upon slope position, soil texture, and hydrology (Jorgenson *et al.*, 2001). Permafrost degradation in peatlands generally results in thermokarst and increased saturation of surface peat, as peat surfaces collapse to levels at or below the water table during thaw. The formation of saturated open fens (called collapse scars or internal lawns) in areas of permafrost thaw (Vitt *et al.*, 1994) is associated with increased CH_4 emissions to the atmosphere (Liblik *et al.*, 1997; Turetsky *et al.*, 2002), an important issue for radiative forcing, given that CH_4 is 23 times more effective in absorbing long-wave radiation than CO_2 per molecule on a 100-year time scale (Ramaswamy *et al.*, 2001). Even in unfrozen peatlands, fire has been invoked as a mechanism contributing to peat initiation and paludification in boreal regions, as conditions post-after fire can be more saturated than before burning, with increased runoff and reduced evapotranspiration (Tolonen, 1985). Thus, increasing boreal fires has the potential to stimulate CH_4 emissions on a landscape scale. However, more saturated conditions postfire in permafrost or unfrozen peatlands is likely to serve as a negative feedback to future fire activity, until peat accumulation above the water table allows for the colonization of plants typical of drier peatland communities (Turetsky *et al.*, 2007).

In more upland habitats, permafrost thaw improves drainage conditions and leads to a decrease in the surface soil moisture content (Hinzman *et al.*, 2003) and potentially massive drainage and the loss of aquatic ecosystems (Yoshikawa & Hinzman, 2003). In these circumstances, permafrost thaw is likely to increase the vulnerability of terrestrial ecosystems to burning.

Interactions between land use, climate, and fire regimes may become increasingly important for carbon storage and fluxes in boreal peatlands. Human activities in peatlands that involve drainage or water table drawdown, such as forestry and agriculture, increase the susceptibility of these ecosystems to fire. Fire severity under these conditions also may be exacerbated as evident by catastrophic peat fires in Indonesia (Page *et al.*, 2002).

Fire–climate interactions: is there a tipping point?

Fire-generated smoke may impact regional and probably even global radiation budgets (Simmonds *et al.*, 2005). Forest fire smoke can have a positive feedback on weather and fire activity by promoting lightning ignitions (Lyons *et al*., 1998) and reducing local precipitation (Rosenfeld, 1999). The feedbacks of carbon losses from global fire have the potential to be a major factor in our changing climate. There is the possibility of a positive feedback, whereby a warmer and drier climate will create conditions conducive to more fire. This in turn will increase carbon emissions from fires, which would feed the warming (Kurz *et al*., 1995). Interestingly, Randerson *et al*. (2006) suggest that boreal forest fires over an 80-year period will lead to a net cooling due to multi-decadal increases in surface albedo. However, this study investigated radiative responses to a single fire event that had low C emissions relative to typical boreal fires. Additionally, the albedo effect is likely to be more pronounced in Alaska than in other boreal regions due to a long snow season and low sun angle. For these reasons, we believe that boreal fires are more likely to contribute to net warming rather than net cooling. Fires in the boreal region could have even stronger effects on our climate system if peatlands start to experience deeper burning due to prolonged drought.

Fire management

Organized fire protection in Canada began in the early 1900s after a number of disastrous fire seasons with substantial loss of life and property associated with increasing settlement of forested areas. By the mid-1930s, fire protection was a provincial/territorial responsibility across all of Canada. In spite of growing protection organizations, the expanding use of Canadian forests for both industrial and recreational purposes resulted in large increases in both the number and impact of forest fires across the country. Fire protection capability expanded and modernized over the ensuing decades, and Canada has evolved into a recognized world leader in many aspects of fire management, assisted in no small way by a close connection to a growing forest fire science capacity, particularly within the federal forestry department. Nevertheless, despite major progress in predicting, detecting, and controlling fires, Canadian fire management agencies recognize quite clearly that there are physical and economic limits to further control fire and have come to realize that increasing fire suppression expenditures lead to decreasing marginal returns in terms of escaped fires or area burned. In addition, there are a number of emerging pressures that are expected to, in the very near future, greatly influence fire management practices in Canada. These include climate change, an expanding wildland–urban interface, declining forest health and productivity, competition for the forest land base, growing public awareness and expectations, and a declining forest fire management infrastructure and capability.

Russian forestry evolved from German models and always included a strong program of fire protection. Recognition that protection of the vast Russian boreal zone would require an aircraft-based reconnaissance and suppression capacity led to the beginning of a formal aerial protection program in the early 1930s (Stocks & Conard, 2000). This program expanded dramatically after World War II as surplus aircraft and demobilized military paratroopers became available. Avialsookhrana, the federal forest protection service, began using helicopters extensively in the 1970s. By the early 1990s, Russia had created the largest firefighting system in the world, and this system was largely successful in reducing area burned, particularly around settlements. However, large fires were still commonplace and vast areas of the Russian taiga burned almost annually. Following the collapse of the Soviet system in 1991, fire control budgets were severely reduced, and fire protection in Russia has become largely ineffective. As a result, severe fire seasons with very large areas burned have become commonplace in Russia, particularly in Siberia, over the past 15 years. Despite the fact that Russia currently receives huge revenues from the global export of its natural resources, none of this is being used in improving forest protection. In addition, forest exploitation is rampant, further exacerbating an already critical fire problem (Goldammer, 2006).

Future fire activity

Numerous research studies have used General Circulation Models (GCMs) to simulate the future climate; these models include three-dimensional representations of the atmosphere, ocean, cryosphere and land surface, and the parameterizations of the associated physical processes. Future climate scenarios are built based on the effects of various concentrations of greenhouse gases and other pollutants within the atmosphere on our earth–atmosphere system. Transient simulations are available from GCMs which allow examination of the possible rates of change in the climate. The major areas of uncertainty in GCMs include clouds and their radiative effects, the hydrological balance over land surfaces and the heat flux at the ocean surface. Despite these uncertainties, GCMs provide the best means available to estimate the impact of changes in the future climate on the fire regime at larger scales. Most models predict the greatest warming at high latitudes in winter. Confidence is lower for estimates of precipitation fields, but many models suggest increased moisture deficits, particularly in the center of continents during summer. In addition to temperature and precipitation, other weather variables such as atmospheric moisture (e.g., specific humidity), wind, cloudiness, etc. will be altered in a changed climate. However, temperature appears to be the most important variable, as increased temperatures lead to drier fuels due to increased evapotranspiration unless there are significant increases in precipitation (Flannigan *et al*., 2005). The variability of extreme events may also be altered (Mearns *et al*., 1989; Solomon & Leemans, 1997) which could have a significant impact on fire activity as many of the largest fires occur on a few critical days with extreme fire weather (Flannigan & Wotton, 2001).

Many studies have addressed the impact of climate change on fire weather severity. Flannigan & Van Wagner (1991) compared seasonal fire severity rating values (Seasonal Severity Rating – it is a rating index to provide a measure of fire control difficulty and is a component of the Canadian Forest Fire Weather Index System) from a $2\times CO_2$ scenario (mid-21st century) vs. the $1\times CO_2$ scenario (approximately present day) across Canada. Their study used monthly anomalies of temperature and precipitation from three GCMs [Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), and Oregon State University (OSU)]. The results suggest increases in the Seasonal Severity Rating across all of Canada, with an average increase of nearly 50%, translating roughly into a 50% increase of area burned. Stocks *et al*. (1998) used monthly data from four GCMs to examine climate change and forest fire potential in Russian and Canadian boreal forests.

Forecast seasonal fire weather severity was similar for the four GCMs, indicating large increases in the spatial extent of extreme fire danger in both countries under a $2\times CO_2$ scenario. Stocks *et al*. (1998) also conducted a month-to-month analysis, which showed an earlier start to the fire season and significant increases in the area experiencing high to extreme fire danger in both Canada and Russia, particularly during June and July. Flannigan *et al*. (1998) used daily output from the Canadian GCM to model potential fire danger through the use of the Canadian Fire Weather Index (FWI) (the FWI is a dimensionless relative numerical rating of fire intensity used as a general index of fire danger) for both the $1\times CO_2$ and $2\times CO_2$ scenarios for North America and Europe. Most of these studies showed large regional variation in the response of fire weather severity to climate change, ranging from significant increases to regions of no change or decreases in fire weather severity (e.g., Bergeron & Flannigan, 1995; Flannigan *et al*., 2000). Consequences of climate change on fire disturbance must be viewed in a spatially dependent context. Only a few studies have quantified the potential changes in area burned due to climate change. Flannigan *et al*. (2005) used historical relationships between weather/fire danger and area burned in tandem with two GCMs to estimate future area burned in Canada (Fig. 3). The results suggest an increase of 74–118% in area burned by the end of this century. Price & Rind (1994) suggest that lightning-caused fires would increase by 44%, while the associated area burned would increase by nearly 80% by the end of the 21st century in the USA. Bergeron *et al*. (2004) discuss implications of a changing fire regime on sustainable forest management in Canada. They find that estimates of future fire activity this century are less than the historical fire activity (preindustrial) for many sites across the boreal forest and suggest that forest management could potentially be used to recreate the forest age structure of fire-dominated preindustrial landscapes. There are other factors such as ignition agents, length of the fire season, and fire management policies, which will likely greatly influence the impact of climate change on fire activity. Ignition probabilities may

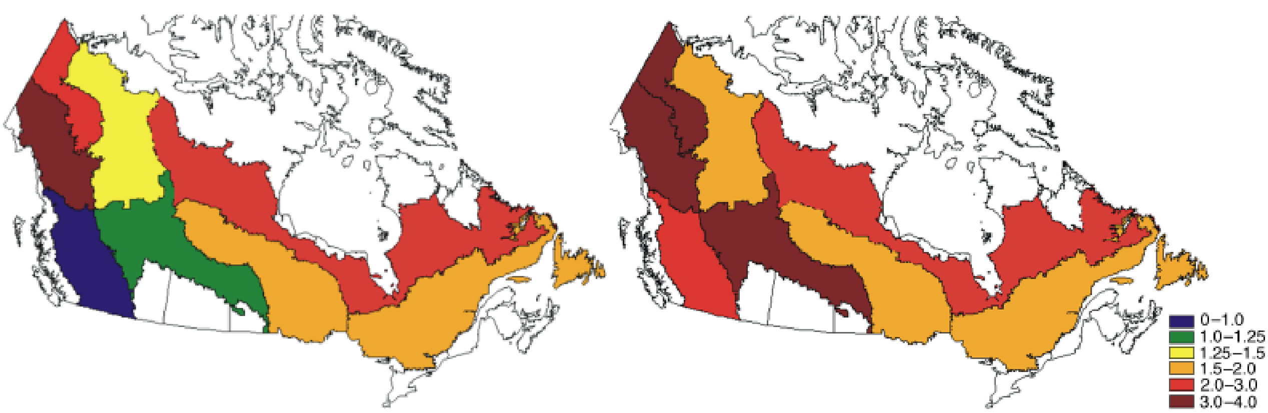

Fig. 3 Ratio of $3\times CO_2/1\times CO_2$ area burned by ecozone using the Canadian and Hadley GCMs, respectively. N/A, not applicable. The area burned model did not work for one ecozone for the Canadian GCM (reprinted with permission from *Climatic Change*).

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increase in a warming world due to increased cloud-to-ground lightning discharges (Price & Rind, 1994), although they did not account for changes in vegetation, which may greatly influence the lightning ignitions and area burned.

Projected changes in fire weather due to climate change have been used to examine resultant changes in fuel moisture and consequently changes in fire occurrence rates in parts of the Canadian boreal forest. Both human and lightning-caused fires are strongly influenced by moisture in the fuels of the forest floor (Wotton, 2008), although both ignite through different processes and should be considered separately in analysis of future fire occurrence potential. Apart from the obvious need for human activity to provide an ignition source, human-caused fire occurrence is most strongly influenced by the receptivity of surface litter to ignition. Wotton *et al*. (2003) carried out a detailed study of future human-caused fire occurrence using daily projections of fire weather and fuel moisture from two GCMs (CCC GCM2 and HAdCM2), which showed that while changes in human-caused fire occurrence vary spatially across the province, overall a 18% increase is expected by the year 2020 and a 50% increase by the end of the 21st century. In an extension of this work, Wotton (2001) showed that future fire weather scenarios for western Canada from a Regional Climate Model (CRCM II; Laprise *et al*., 2003) projected similar increases in human-caused fire activity (46%, 38%, and 25% for the forested areas of the provinces of Alberta, Saskatchewan, and Manitoba, respectively).

While human-caused fires make up just over 50% of the fires occurring in Canada, it is lightning-caused fires that tend to be the major contributor to area burned in the boreal forests of Canada (Stocks *et al*., 2002). Lightning fire ignition is strongly influenced by the moisture content in the organic layers of the forest floor. Wotton *et al*. (2005) examined lightning fire occurrence using fire weather and fuel moisture scenarios derived from the CCC CGCM2 and found a projected increase in lightning fire activity of 24% by 2040 and 80% by the end of the 21st century. This analysis used the relatively conservative approach of using monthly anomalies to generate fire weather scenarios (following the method of Stocks *et al*., 1998), did not account for a lengthening fire season, and did not include changes in lightning activity; thus it was hypothesized that these projected increases in fire activity were quite conservative. The exposure of large areas of previously frozen and wet peatlands to fire is expected to increase significantly as a result of climate change. In addition to the increase in emissions and carbon loss associated with more peatland burning, there is also a growing concern that fires will burn more deeply in exposed organic material, greatly increasing fire suppression difficulties. Much more time and effort would be required to extinguish such fires, thus occupying resources that might otherwise be used to attack new fires. In addition, there is the very real possibility that holdover fires (fires that continue to smolder under snow cover during the winter and reappear the following spring) could become much more common with more peat fires.

Climate warming is expected to make fire seasons longer. Wotton & Flannigan (1993) estimated that the fire season length in Canada, on an average, will increase by 22%, or 30 days in a $2 \times CO_2$ world. Also, research has suggested that the persistence of blocking ridges in the upper atmosphere will increase in a $2 \times CO_2$ climate (Lupo *et al*., 1997), which could have a significant impact on forest fires, as these upper ridges are associated with dry and warm conditions at the surface and are conducive to the development of large forest fires (Skinner *et al*., 1999, 2001).

Fire management policies and effectiveness will continue to change. Changes in prevention programs, initial attack capabilities, and restricted access/fire restriction policies will influence potential fire activity in this century. These other factors are all confounding effects that may dampen or amplify the impact of a changing climate on the fire regime.

Future fire management options

A lengthening fire season, increased fire occurrence, increased fire intensity, area burned, and smoldering combustion in deep organic layers all increase pressure on fire management agencies that have adapted themselves and their resources to respond to the current general level of fire activity. Even today, when conditions become extreme, the increase in fire activity can overwhelm fire management agencies and lead to significant areas burned and losses of timber and property. It has recently been formally recognized in Canada, through the development of the Canadian Wildland

Table 2 Percentage increase in mean annual cost, number of escaped fires, and area burned in the intensive and measured protection zone (adapted from Wotton *et al*., 2005)

	Percentage increase	
	2040/2000 (%)	2090/2000 (%)
Fire occurrence	15	50
Escaped fires	30	80
Fire management cost	16	54
Area burned	31	78

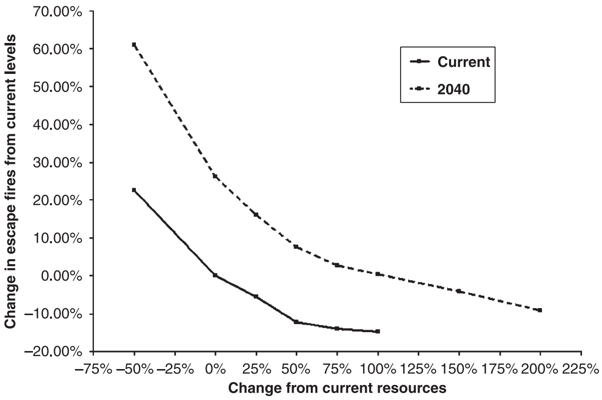

Fig. 4 Change in the number of escape fires (from current level) with changes in resource levels for both current and $2 \times CO_2$ climate.

Fire Strategy (CCFM, 2005), that for management agencies to be able to respond to changes due to climate change (and other pressures such as expanding settlement of the wildland–urban interface), significant changes must occur in the way fire is managed throughout the forests of Canada. Detailed regional analyses support this conclusion. Wotton *et al*. (2005) used future fire weather, fuel moisture, and fire occurrence scenarios (from CCCC CGCMII) coupled with Ontario's level of protection analysis system (LEOPARDS; McAlpine & Hirsch, 1999) to examine the influence of climate change on Ontario's initial attack system. The results (summarized in Table 2) showed a projected increase in escape fire rate greater than the expected increase in fire activity alone, reflecting the inability of the present system to handle the increased fire load (from increased occurrence and increased fire growth). Further analysis of the impact of changing resource levels in Ontario with the LEOPARDS system and the 2040 climate change scenario showed that current provincial suppression resource levels would have to be more than doubled above current operational levels to achieve an escape fire percentage similar to that currently attained by the province (Wotton & Stocks, 2006; Fig. 4). In a similar sort of analysis for northern California, Fried *et al*. (2004) found that increased fire severity in a $2 \times CO_2$ climate scenario produced faster spreading and more intense fires, which led to increases in escape fires by 50–125% over current levels.

Clearly, there will be more boreal fire in the near future, with potentially huge impacts at national to global scales. The ability of boreal countries to effectively mitigate projected impacts at a large scale is severely restricted at best, with fire protection capabilities in North America at their effective physical and economic limits, and Russian fire management in a state of disarray. Adaptation to the emerging reality of more frequent and severe fire impacts will likely include the recognition that our current ability to manage fire will be greatly compromised in coming decades. This would likely result in a gradual reassessment and realignment of protection priorities wherein natural fire is permitted over larger areas, while intensive protection efforts will focus more narrowly on high-value areas and resources. Adaptation at this scale would also require a new policy paradigm, likely driven by greater public awareness/involvement and political will.

The circumpolar boreal zone has recently become recognized as a region of significant global importance, particularly in terms of climate change impacts and carbon storage. Forest fires are the prominent disturbance regime in boreal forests and are expected to increase in both frequency and severity with ongoing and anticipated climate change, with major economic and carbon budget impacts. Projecting future fire regimes under a changing climate requires a baseline of recent fire activity that can be coupled with future climate models to predict future fire frequency, severity, and impacts.

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