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Fire in managed forests of eastern Canada: Risks and options

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ABSTRACT

In this era of climate change, understanding past and predicting future fire activity are scientific challenges that are central to the development of sustainable forest management practices and policies. Such objectives, however, are difficult to achieve for several reasons. Uncertainties about future fire activity can be superimposed on the short time period covered by existing meteorological data and fire statistics, from which a historical range of variability can be determined. Regional fire activity is also tremendously variable over time, such that contemporary fire records cannot provide information on the full range of fire activity variability a given forest experienced and adapted to. This factor is increasingly important when it comes to determining the resilience of boreal forests to changes in climate and disturbance regimes. In this paper, we present a synthesis of past, present and future trends in seasonal fire danger and fire activity based on data gathered in eastern Canadian boreal forests over the last 20 years, and we provide a critical assessment of the ability to conduct sustainable forest management over the 21st century. The data synthesis provides compelling evidence of a synchronous pattern of decreasing fire-conducive climatic conditions and activity of large fire seasons over the last 2000 years in the eastern coniferous boreal forest. Model simulations suggest that the climate will become drier in upcoming decades, driving future fire activity close to the upper bound of the pre-industrial range of variability. The effects of increasing fire incidence cumulated with forest harvesting may thus pose a risk to forest resilience in the future. This ecological knowledge should help us to define forest management strategies and practices considering future fire activity changes forecasted under climate change. Development of alternative silvicultural interventions that would emulate secondary disturbances (e.g. wind, insects) rather than fire would be necessary to maintain pre-industrial forest characteristics (e.g. composition and age class distribution), and associated forest resilience.

1. Introduction

A proposed means to reconcile a rational use of forest resources with the need to preserve long-term ecosystem functionality consists of the application of forestry practices that reduce differences between natural and managed landscapes (Franklin, 1993; Hunter, 1993; Attiwill, 1994; Kuuluvainen, 2002; Gauthier et al., 2009). To maintain biological diversity and essential ecological functions, this forest ecosystem-based approach promotes management interventions that favor landscape compositions and structures similar to those characterizing natural ecosystems. In a system such as the boreal forest where wildfire is a primary natural process that organizes the physical and biological attributes of the forests, the applicability of the ecosystem-based approach requires sound knowledge of disturbance regimes. This includes knowledge of historical fire characteristics (i.e. size of fires, annual burned area, fire return intervals, etc.), and knowledge of their past, present and future drivers. With this information in hand, substitution of fire by harvesting becomes possible if the cumulated disturbed areas due to natural and human-made processes vary within the natural range of variability experienced during the pre-industrial era. In practice, application of ecosystem-based management requires that fire suppression efforts be effective at reducing the rate of disturbances in order to allow substitution by harvesting, or that some other factors like climatic changes,

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species turnovers, and landscape fragmentation directly contribute to reducing the rate of disturbance.

Canadian fire statistics gathered from fire agencies impose inherent difficulties from a forest management perspective. These statistics cover at most a period of 100 years and in many boreal regions, accurate fire statistics have only existed since the late 1970s (Podur et al., 2002), creating several challenges to their use for defining ecosystem management targets. One difficulty with the ecosystem-based approach relates directly to the absence of data on past fire characteristics, which are necessary for its application. A second limitation relates to the ability to assess the risks of infrequent large disturbance events (e.g. Armstrong, 1999; Li, 2002; Hu et al., 2006; Kuuluvainen, 2009; Whitlock et al., 2010; Metsaranta, 2010). For instance, in black spruce – feather moss forests of eastern Canada, a domain covering 412,400 km^2, 45% of the total burned area during the period 1973–2007, was accounted for by 26 fires of size >32,000 ha. These represented at most 2% of the entire fire size distribution (Ministère des Ressources naturelles et de la Faune du Québec (MRNFQ), 2007; fires <1 ha excluded from the statistics). The influence of these infrequent fires on landscape structure and composition is disproportionally high compared with median sized (i.e. typical) fire events, which in these forests are roughly 12 ha. The infrequent nature of these events coupled with the short period covered by the fire statistics create major uncertainties in metrics of central tendencies used in management planning (Whitlock et al., 2010).

Finally, other challenges with existing fire statistics reside in the assignment of temporal trends and attribution of causal factors. Many effects are confounded in fire statistics, including those of changing fire reporting and suppression practices and climatic changes (Podur et al., 2002; Woolford et al., 2010). Additional forcing may also arise from short- and mid-term trends driven by periodic climatic fluctuations, for instance those of El Nino and La Nina (e.g. Skinner et al., 2006). It is thus inherently difficult to relate trends in climate, increased weather variability, or some other factors like increased suppression efforts, to trends in fire statistics. While on a very large scale it is possible to assign causal factors to observed trends in fire activity (Gillett et al., 2004; Macias Fauria and Johnson, 2006), at a regional scale the results may be bounded by major uncertainties and subject to debate (e.g. Cumming, 2005; Woolford et al., 2010).

Forest managers, in their application of the ecosystem-based approach, often have to rely on some other indicators of past fire regimes, the most often in Canada being the method of reconstructing landscape fire history from dendrochronological dating of forest stands (i.e. stand-replacing fire history; e.g. Johnson, 1992). With these fire reconstructions, one will nevertheless face other challenges when trying to attribute observed patterns of fire variability to effects resulting from fire suppression efforts, landscape fragmentation, and climatic changes. Meteorological records used to deduce fire and climate relationships are quite contemporary themselves, such that investigations of this type of relationship rely at most on a few decades of data in the Canadian boreal forests.

A key need for an effective ecosystem-based approach is thus to improve our understanding of the variability of past fire activity and its linkage with climate, ecosystems, and humans. This implies being able to adequately provide answers to these questions: What are the risks of seeing cumulated natural and human-made disturbances exceed the natural range of variability? How have these risks evolved over time and if so, what are the drivers of these changes? Finally, can the risks be offset? This knowledge will inevitably lead to a better understanding of what will be the risks by the end of this century and will allow managers to plan ahead for sustainable forestry. These challenges led to the necessity to conduct multiple-proxy based reconstructions of past fire disturbances, vegetation and climatic changes, and comparison with model simulations of the past and future for mechanistic understanding of drivers of past and future changes in fire activity (Brubaker et al., 2009; Hély et al., 2010a; Pechony and Shindell, 2010). This path is an analogue to that undertaken by the climate community in assigning the sensitivity of global temperature changes to increasing atmospheric greenhouse gases (e.g. Frank et al., 2010; Schmittner et al., 2011).

In this paper, we present a synthesis of past, present and future trends in seasonal fire danger and fire activity based on data gathered in eastern Canadian boreal forests over the last 20 years. We provide a critical assessment of the ability to conduct sustainable forest management over the 21st century considering future climatic changes. We used contemporary fire danger indices (ca. 1901–2002), dendroecological fire reconstructions (ca. 1800–2000), tree-ring based reconstructions (1200–2000) and sedimentary charcoal and lake-level records (ca. 7000 calibrated years before present, hereafter cal yr BP) to document recent and long-term changes in fire activity and climatic conditions. The underlying mechanisms linking fire activity to climatic controls are validated through simulation experiments covering the last 7000 years conducted using a general circulation model. For the future, we used predictions of fire activity derived from ensemble means of general circulation model experiments and greenhouse gas emissions scenarios. The synthesis is divided into four sections. The first three sections address perspectives of historical and future fire risks from the analysis of the different types of fire reconstructions and predictions. In each case, brief reviews of methods and analyses are presented. Finally, in Section 4 we review adaptation options covering the strategic and silvicultural aspects of forest management in light of predicted future fire risks.

2. Diagnostic of ongoing changes in Canadian fire activity

The application of ecosystem-based management in boreal forests requires that the impact of natural disturbances be reduced as compared with the past in order to allow substitution by harvesting. This requirement raises an important question that has attracted increasing attention in the fire literature over the past 15 years (Girardin et al., 2010): is boreal fire activity changing with ongoing climatic and environmental changes? With a dynamic climate and the strong linkage between climate, weather and forest fires, variations in historical observations of fire activity due to changes in moisture regimes can be expected (Van Wagner, 1987; Flannigan and Harrington, 1988). However, as indicated earlier, many other factors may influence fire activity, including land-use changes and increasing fire suppression efforts (Marlon et al., 2008; Pechony and Shindell, 2010). These confounding influences have led authors to suggest that fire suppression during the past 50–80 years has contributed to changing the recurrence of fire in many regions of Canada (e.g. Mouillot and Field, 2005; Pechony and Shindell, 2010) and Scandinavia (e.g. Niklasson and Granström, 2000).

In Canadian forests, little was known until recently about long-term changes in spatial and temporal patterns of fire-conducive climatic conditions. This knowledge is of central importance for the application of the ecosystem-based approach in these forests. If current fire activity remains under climatic control in spite of all other factors, then more severe fire-conducive climate conditions in the future could impact our ability to conduct sustainable forestry. In this section, we provide a summary of recently acquired information on fire activity and fire danger in Canadian forests, and develop a data comparison to evaluate the extent to which changing fire activity is under climatic control.

2.1. A meta-analysis of Canadian fire history studies

We first illustrate our point using previously published fire syntheses by Bergeron et al. (2004a) and Gauthier et al. (2009) in which historical (i.e. pre-industrial era) annual proportions of burned areas were compared with current ones. Historical (the last 200 years or so) fire metrics were determined from a literature review of 28 fire studies mostly distributed in managed forests in eastern and western Canada (Fig. 1). In most cases, historical fire data were obtained from post-fire stand initiation reconstructions created using field and archival data digitalized and included in GIS databases. While recent fires were precisely dated and mapped, years and area burned of older fires were generally estimated by dendrochronological dating and interpolation. Current (period 1959–1999) proportions of burned areas were estimated at each location from the Canadian large fire database that includes all fires larger than 200 ha (Stocks et al., 2003). Historical and current fire cycle estimates (i.e. the time required to burn an area equivalent in size to the study area) were computed and converted into annual proportions of burned areas. For the purpose of this synthesis, a metric δ_g that captures the changes in fire activity between the two periods was calculated as follows:

$$\delta_g = \frac{b_{CURRENTg}}{b_{PASTg}} \quad (1)$$

where $b_{CURRENTg}$ and b_{PASTg} are current and historical proportions of annual burned areas, respectively, at a given location *g*. Values of δ_g above 1.0 are indicative of a higher incidence of fire activity in recent decades as opposed to the historical period, and vice versa.

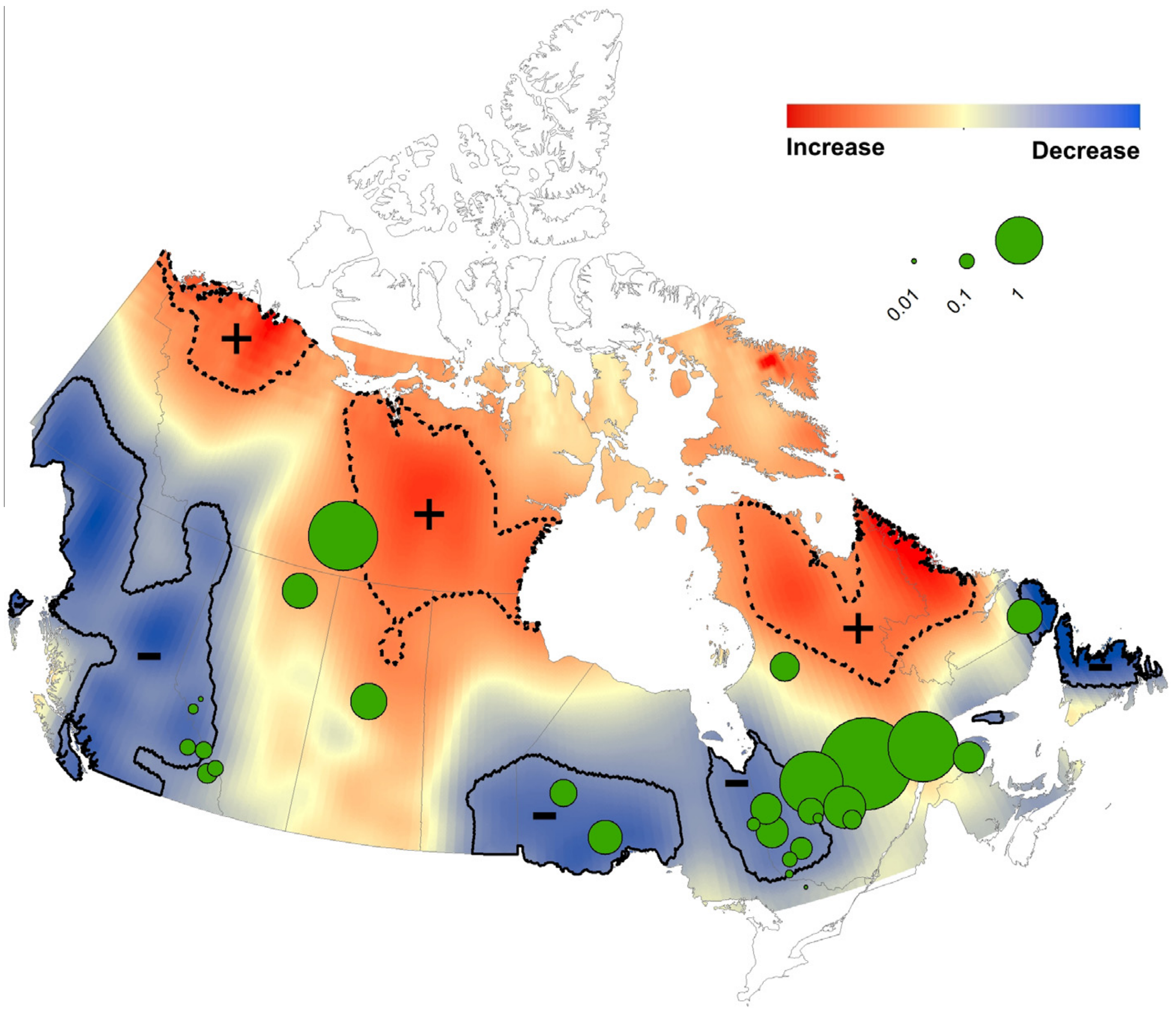

Fig. 1. Locations of the 28 fire histories across Canada's forests considered in this synthesis and map of trends in seasonal fire danger between 1901 and 2002 modelled using the July Monthly Drought Code (MDC; see Girardin and Wotton, 2009 for details). The circle size corresponds to the magnitude of the ratio δ_g of the current (1959–1999) to past (pre-industrial era) proportions of annual burned areas (unitless) at each location (smallest symbols: ratio < 0.01; largest symbols: ratio > 1.00; median symbols size: ratio = 0.30). The MDC analysis only considers climate variability and does not include other factors such as fire suppression and ignition, vegetation changes, etc. Areas of increasing and decreasing fire danger from 1901 to 2002 are denoted by plus and minus signs (and red and blue colors), respectively. Contoured areas passed the 5% level for significance of linear trends (solid lines for positive trends; dashed lines for negative trends). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As reported by previous studies, 24 of the 28 locations have had historical fire activity superior to current estimates (Fig. 1). Southwestern and -eastern locations had the most dramatic decreases in fire activity with the lowest δ_g values. At northern locations, δ_g values tended to be closer to 1.0 (slightly above or below). Hence, there has been a widespread continental decrease in fire activity from the pre-industrial to the current eras.

2.2. Insights from high-resolution gridded climatology

While the finding of a widespread decline of fire activity is not a new one (e.g. Masters, 1990; Larsen, 1997; Bergeron et al., 2001; Tardif, 2004; Wallenius et al., 2011), it has never been attempted before to relate these patterns of change to climatological information. Recently, Girardin and Wotton (2009) assessed trends in fire danger across Canada with a Canada-wide analysis of 20th century linear trends in the Monthly Drought Code (hereafter called MDC) and on a high-resolution gridded climatological dataset (0.5° latitude by 0.5° longitude grid of the Climate Research Unit (CRU) TS 2.1 data; Mitchell and Jones, 2005). The MDC is a fire danger index that takes into account effects of evapotranspiration and precipitation on cumulative moisture depletion in deep organic layers. It is a generalized monthly version of the daily Drought Code (DC) widely used across Canada by forest fire management agencies in their monitoring of fire danger, and represents the moisture content of an organic layer that is on average about 18 cm thick and 25 kg m^{-2} dry weight, for a bulk density of 139 kg m^{-3}. The maximum theoretical moisture content of the fuel roughly corresponds to the water-holding capacity of soil, i.e. 100 mm (Van Wagner, 1987). High MDC and DC values are indicative of high fire danger. Girardin et al. (2009) and Balshi et al. (2009) showed that the two fire danger metrics for the month of July had significant predictive skills for annual area burned across circumboreal forests.

Observation of changes in July MDC reveals unexpected heterogeneity of drying rates in the deep layers of the forest floor of Canadian forests: climate is a dynamic system and changes in its properties are unevenly distributed in time and space (Fig. 1). The fire danger declined south of Hudson Bay, in western Canada and in the eastern Maritimes. These regions have experienced significant increases in summer precipitation, which have contributed to increasing moisture content in deep-organic layers (Girardin et al., 2009; Meyn et al., 2010). On the other hand, in the taiga (or open northern boreal forest) the fire danger increased, largely an effect for increasing summer temperatures and the potential evapotranspiration experienced by these regions in recent decades (Trenberth et al., 2007; Girardin et al., 2009). The consistency between changing fire danger and the fire metric δ_g that captures the changes in fire activity between the current and historical periods is striking: from the 24 locations showing a decrease in fire activity, 21 had recorded a decline in fire danger during the 20th century (Fig. 2). Two locations in which fire activity has significantly increased have also recorded an increase in the MDC (sites located in Rutledge Park, northern Alberta, and on the north shore of the St. Lawrence River, Quebec; data respectively from Johnson, 1979 and Cyr et al., 2007).

At only five locations, ratios δ_g were clearly inconsistent with trends in MDC (Fig. 2). Several explanations may be put forward for these inconsistencies, including the sparse distribution of long-term running meteorological stations in northern boreal regions that may have affected the trend analysis in climatic data. Changes in the occurrence rates of extreme drought years that occur independently from the long-term trends in average conditions may also explain patterns of divergence (Girardin et al., 2009). Additionally, the sources of information extracted from two different spatial units may have induced some errors in the comparison

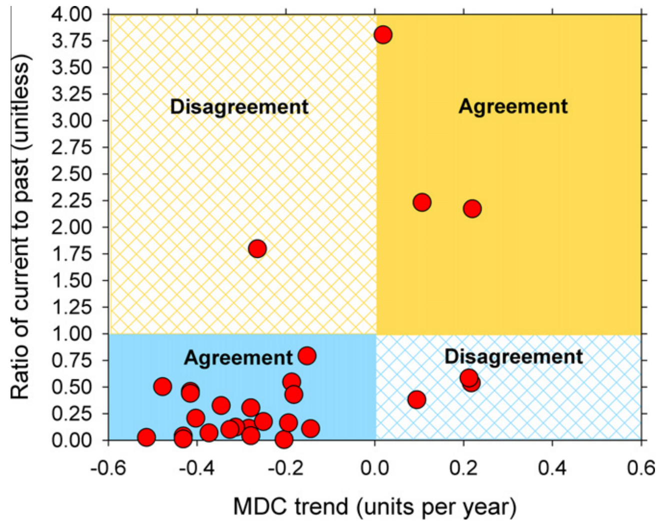

Fig. 2. Ratio δ_g of current (1959–1999) to past (pre-industrial era) proportions of annual burned areas plotted against the slope of the linear trend in the July Monthly Drought Code (MDC) fitted over 1901–2002 at 28 locations across Canada's forests. Refer to Fig. 1 for details and definitions. Shaded and hatched areas delineate those ratios of current to past proportions of burned areas that are in agreement and disagreement, respectively, with observed trends in fire danger (23 agreements and 5 disagreements). The Spearman rank correlation is 0.56 ($P < 0.010$).

of the past to current fire metrics. Past fire metrics were deduced from small areas compared with those used for computation of the current fire metrics, and hence may be biased by particular local factors like forest and soil types. This may be the case for the site showing the highest ratio δ_g (site located in the vicinity of Saguenay-Lac-Saint-Jean, Quebec; data from Bélisle et al., 2011). Furthermore, in many regions there is either a distinctly thin or absent duff layer. Under such conditions, trend analysis of July MDC is arguably questionable, and indices with shorter drying lags are likely to be better for evaluating climatic change impacts on fire activity (see Balshi et al., 2009). Other factors have evolved in importance over the past century and may have obscured the comparisons of trends between MDC and fire activity. These factors include changes in wind velocity and their impacts on fire behavior (Li et al., 2000), changes in fire seasonality (Kasischke and Turetsky, 2006), changes in ignition agents (lightning frequency and human-caused ignition; Price and Rind, 1994; Wotton et al., 2003), changes in land use (e.g. fragmentation of landscapes and fire suppression; Niklasson and Granström, 2000; Lefort et al., 2003; Cumming, 2005), interactions with other natural disturbance agents such as insect outbreaks and diseases, and higher fire activity during the fur trade period caused by the native Americans and European settlers (Wallenius et al., 2011). There is clearly a need for additional analyses if we are to successfully document and attribute long-term wildfire trends in these forests.

3. Recent advances in paleoecology and paleoclimatology in eastern boreal Canada

Patterns and controls of fire behavior have interested scientists and land managers for over a century (e.g. Bell, 1889; Nesterov, 1949; Lutz, 1956; Johnson, 1979; Harrington et al., 1983), and extensive bodies of work have been produced on both the climatic and vegetation controls on wildfires (see literature review by Macias Fauria et al. (2010)). Recent developments have evolved to avoid statistical limitations imposed by the short temporal depth of meteorological and fire records in assigning a relationship between patterns of fire activity and climatic changes (e.g. Marlon et al., 2008; Hély et al., 2010a,b; Wallenius et al., 2011). Knowledge was gained using a large array of different data, approaches and methodologies, thereby providing a robust assessment of how the contemporary era fits into the long-term perspective. This information is relevant for sound boreal-forest management since the long history of varying ecological and climatic conditions provides knowledge about the resilience of boreal forests to disturbances (Carcaillet et al., 2010) while also providing information on past historical ranges of variability used for forest management planning (e.g. Cyr et al., 2009). Below we show some recent advances in our understanding of long-term fire and climatic controls as highlighted by the analyses of ecological data, with a focus on eastern Canada.

3.1. Cross-comparison of fire history and tree-ring based fire predictions

Recent achievements in fire science include the development of statistical predictions of past regional fire activity variability deduced from the extensive analysis of tree rings (e.g. Westerling and Swetnam, 2003; Knapp and Soulé, 2011). Through statistical modelling, it is possible to predict past fire metrics like annual burned areas and fire occurrences from a network of well replicated tree-ring records. Here tree-ring records are defined as averages of annual ring width or density measurements for one to several radii per tree and from a sample of trees (typically ~20) growing on similar ecological sites. The methods employed in the development of these fire predictions are similar to those used in climatology when inferring about past temperatures (Fritts, 2001), and have for a rationale that trees are sensitive to climatic variability conducive to fire activity. This may be the case for variations in the amplitude of the major belt of westerlies that give rise to patterns of high- and low-pressure systems and their incidence on severity of fire weather indices (Girardin and Tardif, 2005). After ensuring that the tree-ring records are adequate candidates for inferring the targeted fire metrics, a stepwise multiple regression may be used to fit a linear model relating annual burned areas, for instance, to a set of tree-ring width records over their common period,

$$y_j = \alpha + \beta_1 x_{1j} + \beta_2 x_{2j} + \beta_m x_{mj} + \varepsilon_j \quad (2)$$

where y_j is the total annual burned areas, x_j the tree-ring records, β the regression coefficients, and ε_j the error. Once the regression coefficients are estimated, they can be applied to the tree-ring records for as far back as possible to produce a series of predicted annual burned areas. Tree rings can thereby provide information that enhances the limited temporal coverage of observational fire records. Here, there is an important but valuable difference to be made in comparison with traditional fire histories derived from stand initiation maps (Section 2.1): fire predictions deduced from tree-ring records assume that climate is the only driver of past changes in fire activity. Hence, if in a particular region the fire metrics obtained from stand initiation maps are inconsistent with statistical predictions deduced from tree rings (i.e. the two sets of data are uncorrelated), then one can reasonably assume that factors other than climate may be driving the changes in regional fire activity (e.g. Knapp and Soulé, 2011; Wallenius et al., 2011). The reverse also holds true.

Statistical predictions of past changes in the annual number of large fires (size > 200 ha; data from Stocks et al., 2003) in managed forests in eastern boreal Canada covering 1768–1998 offer a valuable opportunity for carrying out a fire data comparison (Fig. 3). These statistical predictions were developed using standard climatological procedures and from a network of 126 well-replicated site tree-ring width chronologies, consisting of over 2000 trees from 13 species, and originating mainly from the Boreal Shield (site tree-ring width chronologies are defined as averages of annual ring width measurements for one to several cores per tree and for several trees growing on similar ecological sites). The fire estimates accounted for 59% of the variance in the observed annual number of large fires recorded from 1959 to 1998 (Girardin and Mudelsee, 2008). While these estimates are centered on drought-driven large fires, they also track down changes that have occurred in the number of drought-driven mega-size fires. For instance, in recent years (1959–1999 period) the proportion of fires that exceeded 32,000 ha (a subjectively set threshold for mega-size fires) was closely related to the overall number of large fires, and overall were also positively related to the occurrence of severe drought conditions (Fig. 4). The statistical predictions of fire activity highlight several episodes of high fire activity in the 1780s, 1800s, 1830s, 1860s, 1910–1930s, and 1960s (10-year median >50 fires). However, these predictions also show a significant decrease in the activity of extreme fire years during the period covered by data (Fig. 3; Cox and Lewis (1966) u-test statistic for trends in extreme events: $P < 0.05$, period 1769–1998). Specifically, predictions indicate 1 year of extreme fire conditions for every 5 years during the 1770–1820s and 1 for every 6 years during the 1920s. During the late 20th century the rate of occurrence of extreme fire years is estimated at 1 for every 14 years.

As benchmarks for a data comparison and for evaluating the climatic controls on fire activity, we used a stand-age distribution developed by Bergeron et al. (2004b) that extends back to the mid-1600s. In agreement with the fire predictions, stand recruitments higher than expected under constant fire activity have occurred during the decades 1770–1840, 1890–1920, and in the 1940s (Fig. 3). The similarities between the stand establishment record and the statistical predictions stand out when comparing the stand age distribution with estimates of occurrence rate of extreme fire years. Ratios of the stand age distribution to the theoretical distribution, which highlights departures in fire activity from the long-term average, are significantly correlated to occurrence rates of extreme fire years (45% of variance in common). Additionally, a scatter diagram of the data (Fig. 5) shows that low fire activity during the late 20th century was predictable on the basis of the climatic factors used in the statistical predictions.

Some long-lived species provide a much longer assessment of changing climatic conditions. Notably, a tree-ring width chronology consisted of white cedar (*Thuja occidentalis* L.) growing on islands in Lake Duparquet and extending into the past as far back as 1200 AD (i.e. 750 cal yr BP) provides independent insights into past drought conditions (data from Bergeron and Archambault, 1993; Girardin et al., 2004). This chronology was recently updated to 2008 by resampling of the original trees. Estimates of the proportions of annual burned areas obtained from the analysis of fire scars on trees collected on the same islands in Lake Duparquet (Bergeron, 1991) may be used for cross-comparison. The white cedar chronology (Fig. 6a) shows evidence of marked variations in growth. Periods of low growth during the 1710s–1850s and 1900s–1920s are consistent with higher rates of occurrence of extreme fire years inferred from the tree-ring reconstruction of fire activity (Fig. 3). A decrease in the proportion of burned area on the Lake Duparquet islands (Fig. 6b), on which fire suppression and land-use changes have never been made due to their small sizes and remote locations (Bergeron, 1991), is consistent with an increase in growth of white cedar, providing another argument in support of climatic control of fire activity in eastern boreal Canada.

3.2. Fire activity during past millennia and the Milankovitch theory

The Milankovitch theory describes the collective effects of changes in the Earth's movements upon its climate, where regular

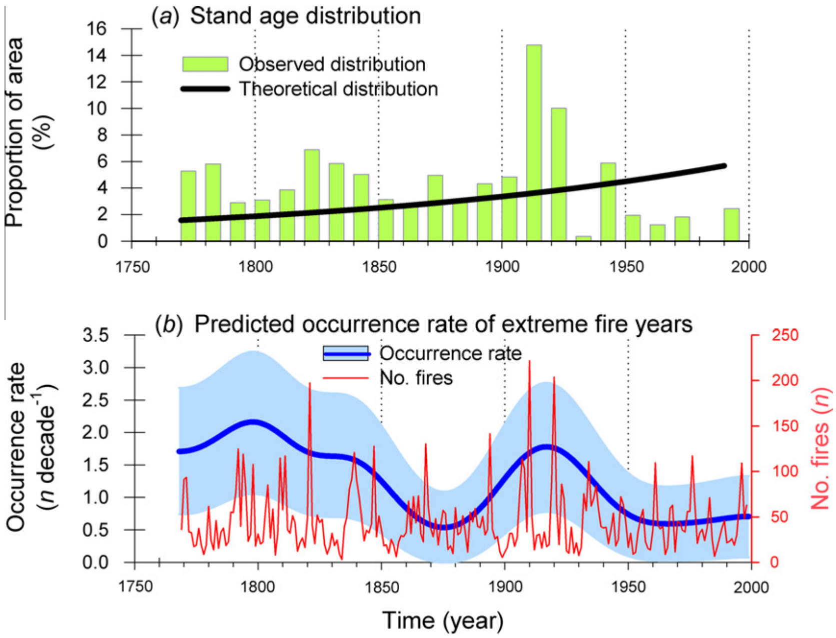

Fig. 3. Late-Holocene fire activity on mainland of eastern boreal North America. (a) Stand age distribution for an area of 15,000 km^2 located at the transition zone between the mixedwood and coniferous boreal forests of southwestern Quebec (vertical bars) in 10-year age classes expressed in % of total study area (data from Bergeron et al., 2004b). The curve shows the theoretical stand age distribution expected under a constant proportion of annual burned areas of 0.58% per year. Values of area burned below the theoretical curve (notably during the late 20th century) are indicative of low fire activity, and vice versa. (b) Predicted annual number of large fires (size >200 ha; red curve) and occurrence rate of extreme fire years (No. extreme fire years per decade; thick-blue curve) in managed forests of eastern boreal Canada, as inferred from tree-ring width records, and associated 90% confidence interval (shaded area) (data from Girardin and Mudelsee, 2008). An extreme fire year is defined as a year in which the predicted number of fires of size >200 ha exceeds the threshold of 75 fires (the equivalent of the 85th percentile of the frequency distribution of all years). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

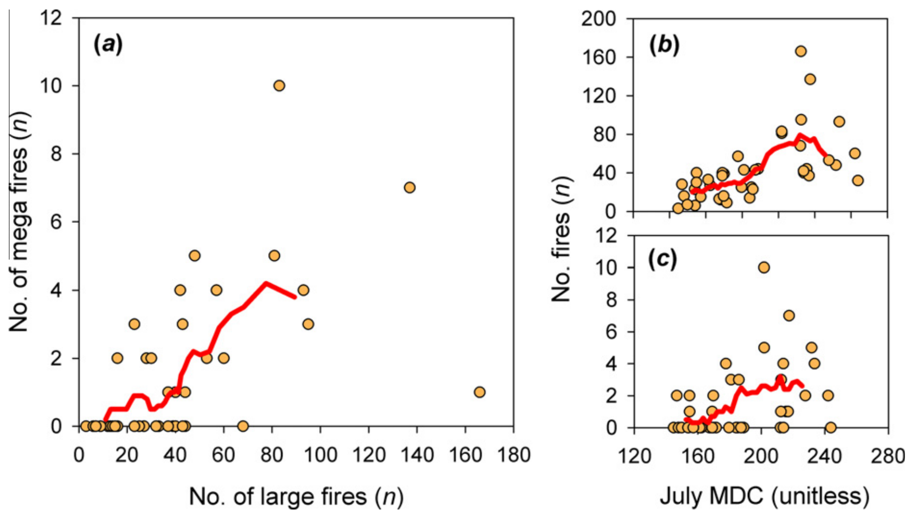

Fig. 4. (a) Annual number of mega-size fires (>32,000 ha) versus the annual number of large-size fires (size > 200 ha) in managed forests of eastern boreal Canada. (b) and (c) Relationship between annual numbers of large and mega-size fires, respectively, and the July Monthly Drought Code (MDC). The thick line is a moving average across a window of 10 observations. The Spearman rank correlation is (a) 0.64 ($P < 0.001$), (b) 0.70 ($P < 0.001$) and (c) 0.45 ($P < 0.010$) ($n = 41$ years). July MDC data were taken from Bergeron et al. (2010); fire data were those of Stocks et al. (2003).

periodicities in the Earth's orbit and tilt influence the amount and distribution of the sun's energy (Hays et al., 1976; Berger and Loutre, 1991). At latitude 45°N for instance, the input of summer solar irradiance has declined by roughly 7% during the course of the last 8000 years (Berger and Loutre, 1991). Simulations of past temperature changes by model simulations and reconstructions of past temperatures from proxy records indicate a millennial-scale summer cooling of −0.22° C per 1000 years during the course of the last 2000 years as a direct response to declining incoming summer solar irradiance at northern latitudes (Kaufman et al., 2009). Recent studies suggested that climatic variability resulting from declining incoming solar irradiance has had a detectable influence on regional fire metrics when analyzed at millennial scales (Hély et al., 2010a; de Lafontaine and Payette, 2011). Peaks in charcoal accumulation in lake sediment records have provided the most important insights into this area of research. Variations in charcoal accumulation rate or influx (charcoal load per time unit, e.g. $mm^{-2}\,cm^{-2}\,yr^{-1}$) provide a continuous record of past local fire activity within the sampling resolution of the sediment record (e.g. Higuera et al., 2007; Ali et al., 2009) that may be used in

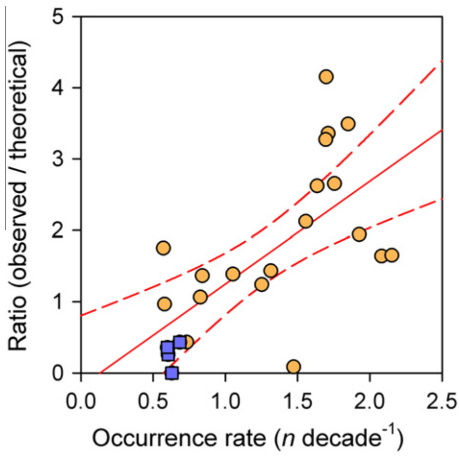

Fig. 5. Cross-comparison of the reconstructed late-Holocene fire activity (ratio of observed stand age distribution divided by the theoretical distributions) and predicted occurrence rate of extreme fire years in managed forests of eastern boreal Canada (see Fig. 3 for details). Number of samples is $n = 23$ decades. Blue squares denote the last four decades under study (e.g. 1960 to 1990). A linear fit with 95% confidence interval is shown ($R^2 = 0.45$, $p < 0.001$; diagnostic of model residuals: Durbin-Watson D statistic = 1.61, constant variance test $p = 0.055$, Shapiro–Wilk normality test $p = 0.907$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cross-comparison with, for instance, pollen-based vegetation reconstructions and model simulations of past climate.

Hély et al. (2010a) recently assessed the orbital influence on fire activity in the managed coniferous forests of eastern boreal Canada through the analysis of charred sediment particles extracted from five kettle lakes located in eastern Canada, at the southern limit of the northern boreal forest, a closed-crown needleleaf vegetation dominated by the fire-prone black spruce (*Picea mariana* (Mill.) BSP). The millennial-scale series of fire occurrences extracted from this analysis was compared with reconstructions of Holocene moisture regimes extracted from lake levels and simulated using outputs from the United Kingdom Universities Global Atmospheric Modelling Program (UGAMP) model. The UGAMP model is a time-dependent numerical representation of the atmosphere and its phenomena over the entire Earth, using the equations of motion and including radiation, photochemistry, and the transfer of heat and water vapor. Such models are now often used for back-casting past climatic conditions so as to increase our understanding of ecological phenomena.

The maximum rate of fire disturbances was recorded from 6000 to 2000 cal yr BP according to the sedimentary charcoal records (Fig. 7a). The onset of the negative trend in fire activity began approximately 2000 years ago and is synchronous to a decline in incoming solar irradiance during summer (Fig. 7b) and simulated fire danger (Fig. 7c). The lake levels were predominantly low between 7000 and 3200 cal yr BP, and higher since 3000 cal yr BP, suggesting most likely an increase in precipitation or a decrease in evaporation and evapotranspiration, with all these conditions being less favorable to fire occurrence (Fig. 7d). The seasonal cycle of solar irradiance was important for past fire activity as it modified the fuel dryness necessary for ignition and fire propagation. The long-term diminishing trend toward present-day low fire activity in coniferous forests of eastern Canada is seemingly attributed to the reduction in summer solar irradiance from 6000 cal yr BP to the present coupled with an increase in annual precipitation.

It is important to note that fire histories in forests that differ significantly from those studied by Hély et al. (2010a) may present different long-term trajectories. For instance, maximum fire frequency was found to occur after 2500 cal yr BP in the southern mixedwood forests, a period corresponding to an increase in coniferous presence in these landscapes as a consequence of a cooler climate (Carcaillet et al., 2001) and a possible change in the frequency of summer drought (Carcaillet and Richard, 2000). Different fire histories from within the same region but under different vegetation types raise

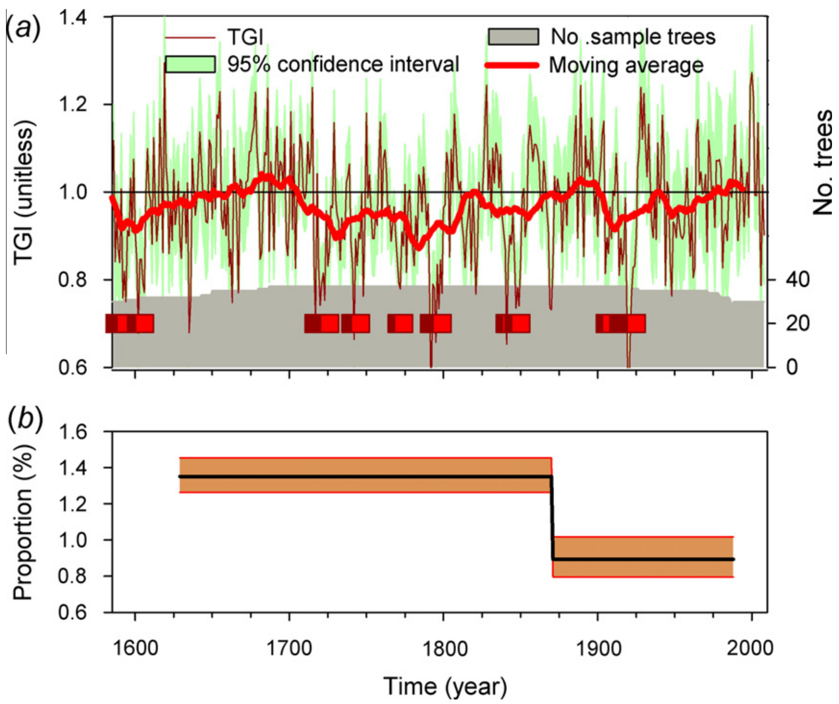

Fig. 6. Late-Holocene fire activity on the Lake Duparquet islands in eastern boreal North America and patterns of ring-width variation in white cedar. (a) White cedar tree-ring growth index (TGI) chronology (data from Bergeron and Archambault, 1993). The shaded area is the 95% confidence interval for the mean of the individual series ($n = 38$ trees); the thick-red line is a moving average across a 30-year overlapping window. Squares mark periods of reduced growth (TGI < 0.90 units for at least 4 years within a 5-year moving window). (b) Proportion of burned area per year on the islands reconstructed from the analysis of fire-scarred trees (data from Bergeron, 1991).

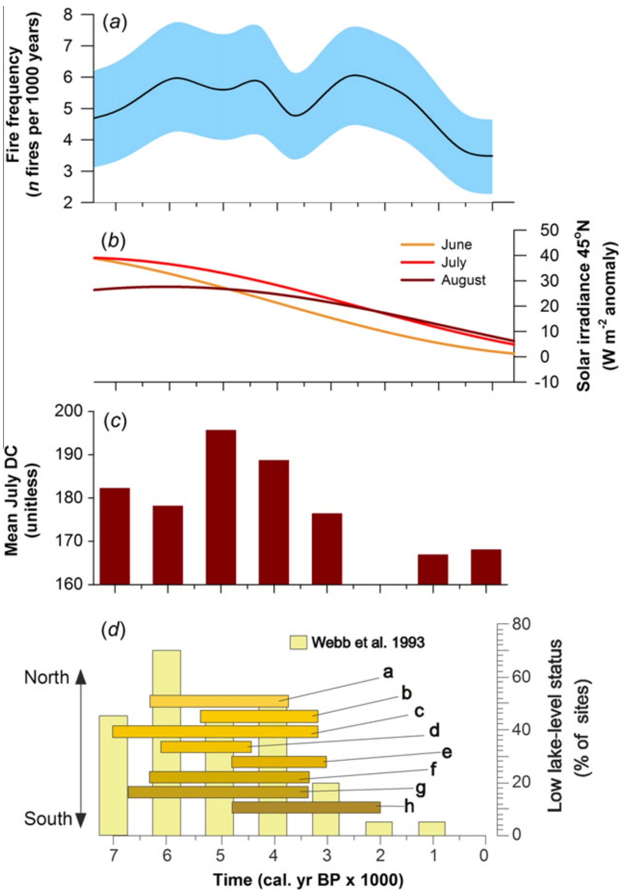

Fig. 7. Holocene fire activity and climate in eastern boreal Canada. (a) Mean local fire frequency in a pure coniferous boreal forest (black spruce–feather moss) deduced from analysis of sedimentary charcoal series from five kettle lakes, with 95% confidence interval. The values may be interpreted as the number of fires per 1000 years that may be encountered in a given forest stand. (b) Summer solar irradiance anomalies computed at 45°N expressed as anomalies relative to 1950. (c) Mean July Drought Code (DC) computed from simulated temperature and precipitation data by the Universities Global Atmospheric Modelling Program (UGAMP) general circulation model (Slingo et al., 1994). High DC values are indicative of high fire danger. Climatic data at 2000 cal yr BP were unavailable. (d) Dryness periods based on low lake-level status inferred from biological remains, and sedimentary and geomorphic evidence from a northeastern North American synthesis (yellow histogram; Webb et al., 1993) and from several studies in eastern Canada plotted from the north (yellow/light-brown) to the south (dark-brown) (a: Payette and Filion, 1993, b: Miousse et al., 2003, c: Moos et al., 2009, d: Lavoie and Richard, 2000, e: Muller et al., 2003, f: Yu et al., 1996, g: Yu and McAndrews, 1994, h: Yu et al., 1997). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

questions about the long-term relationships between air masses, fire and vegetation.

4. A predictable future

Previous sections have indicated that long-lasting periods of high fire activity have characterized the eastern boreal forests over the past and that these periods are linked to long-term climatic changes. Natural climatic variability, which includes that originating from orbital and volcanic forcing and atmosphere–ocean dynamics, have very likely contributed to these trends. If increased fire activity in eastern Canada is a natural response to warmer climates than at present, then any trend toward higher temperatures not compensated for by significant precipitation increases in the future will lead to an increase in the fire risk over eastern boreal North America. Increasing atmospheric concentrations of carbon dioxide linked to human activities have had a significant impact on climate over the past 50 years and this impact is predicted to persist in upcoming decades (Christensen et al., 2007). Projected changes in mean annual temperature and precipitation totals for eastern North America by regional and global climate models for the late 21st century range from 2.5 to 5.5 °C and 4% to 25%, respectively (Plummer et al., 2006; Christensen et al., 2007). Increases in temperature and precipitation are predicted to be higher in winter, and summers will be longer (Plummer et al., 2006; Christensen et al., 2007). Summer droughts are also expected to increase, despite an increase in annual amounts of precipitation (Christensen et al., 2007).

Predictions of changes in fire activity in eastern Canada are mostly obtained by a hybrid modelling approach in which an empirical mathematical model relates fire metrics to variables describing the drying process of the different soil organic layers and to fire behavior (Flannigan et al., 2005; Bergeron et al., 2006; Balshi et al., 2009; Girardin and Mudelsee, 2008). Despite the different modelling procedures and data used, these predictions of future fire activity are largely in agreement and suggest that annual burned areas and fire occurrences will increase by the end of this century (see Flannigan et al., 2009 for a review). Trends will be statistically detectable by the mid-21st century (Girardin and Mudelsee, 2008).

Recently, Hély et al. (2010a) suggested that the projected warming trend associated with increasing concentrations of greenhouse gases in the atmosphere will induce a change in fire risk in the black spruce coniferous forest superimposed on the one already induced by orbital changes, but opposite in sign. Hély et al. (2010a) have hypothesized that fire activity will be brought back toward the upper limit of its historical range, recorded from 6000 to 2000 cal yr BP, when summer temperatures were warmer than present and annual precipitation lower. The resulting trajectory is illustrated in Fig. 8. For the purpose of this synthesis, we made use of the previously published predictions for future fire activity in eastern boreal Canada by Bergeron et al. (2010) and compared them with past fire activity variability inferred from the analyses of charged particles extracted from lake sediments as presented in Fig. 7. Future fire predictions were obtained using simulated monthly temperature and precipitation data collected from an ensemble of seven GCMs and multiple scenarios of

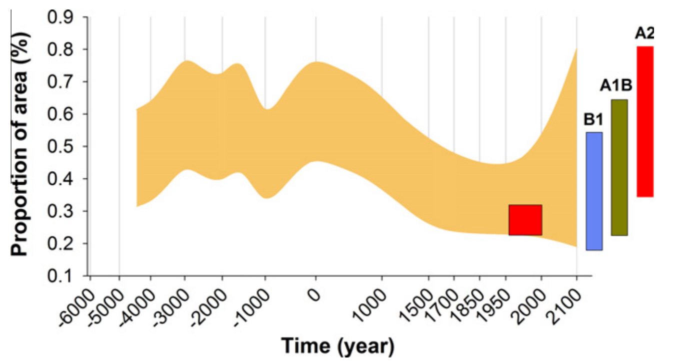

Fig. 8. Past and future changes in fire activity in eastern Canadian coniferous forests (black spruce–feather moss). Past proportions of annual burned area were inferred from analysis of sedimentary charcoal series from five kettle lakes (see Fig. 7; shown is the 95% confidence interval). Future (i.e. 2081–2100; vertical bars) proportions of annual burned area were predicted using an ensemble approach of seven climate models forced by three different storylines of greenhouse gas emissions (IPCC, 2000). From 'worst'- to 'best'-case scenarios with respect to CO_2 emissions: A2, A1B, and B1. The ranges were obtained from the 95% bootstrap confidence interval for the given scenario ensemble-mean of the GCM experiments (see Bergeron et al., 2010 for details). The red square marks the current (1959–1999) proportion of annual burned areas in the black spruce-feather moss forests. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

projected changes in greenhouse gas emissions (IPCC, 2000). As can be observed in Fig. 8, the wide array of scenario outcomes suggests significant uncertainties in future fire activity in regard to the level of the predicted trends. The ensemble mean of all simulations suggests an increase in the proportion of annual burned areas from a current value of 0.22% year^{-1} to 0.45% year^{-1} by the end of the 21st century. A doubling of the fire activity in these forests as predicted by these models is quite plausible when placed in the context of the long-term variability derived from the paleoecological reconstruction. The business-as-usual (A2) scenario outcome attains fire levels similar to historical ones with a mean proportion of 0.55% by the year 2100.

It is important to note that predicted future fire activity is based on empirical models developed from a limited range of values and conditions, and excludes important processes that may feedback onto the climatic drivers. For instance, most models do not consider the feedback effects of vegetation changes on fire behavior (Hessl, 2011). Moreover, vegetation models do not take into account the migration capacity of species (Weber and Flannigan, 1997). Vegetation composition and structure influence fire activity through fuel availability and moisture regimes (Flannigan et al., 2001; Hély et al., 2001). Projected changes in disturbance regimes could lead to changes in the structure and composition of the boreal forest (Bergeron and Dansereau, 1993), which could then have feedback effects on fires (Johnstone et al., 2009; Pechony and Shindell, 2010). Increasing occurrence and severity of fires could lead to an increasing proportion of hardwood species in forest landscapes and to younger forests (Bergeron and Dansereau, 1993; de Groot et al., 2003; Lecomte et al., 2006; Lesieur et al., 2002), which in turn could feedback on the fire sizes (Hély et al., 2010b). Currently, there is no realistic estimate of the future response of vegetation to changing disturbance regimes in eastern boreal Canada. Vegetation records suggest that in eastern Canada, vegetation composition and diversity remain rather inert when faced with natural modifications of the fire activity; most of the changes in vegetation were likely related to progressive changes in climatic features (Carcaillet et al., 2001, 2010; Genries et al., in press).

Additionally, other uncertainties related to the randomness of fire events add up in predictions of future fire activity for eastern Canada. Fire ignition sources are often absent in the development of fire predictive models (Hessl, 2011). The predictions may therefore be incorrect if a significant change takes place in the ignition frequency, particularly in connection with the increased human use of forests. Also, knowledge about effects of changes in the fire season, especially in combination with an early melting of the snow cover, orographic features, and lightning frequency are still unknown (Flannigan et al., 2001; Plummer et al., 2006). Other aspects remain unpredictable. One uncertainty relates to the difficulty of projecting future changes in a chaotic system (such as the climatic one; Rind, 1999) in which the relationships between the various components are not similar in time. Climate models project relatively satisfactory global and regional temperature predictions, while predictions of precipitation are relatively uncertain, particularly because of their random characteristics (Christensen et al., 2007). Up-to-date fire predictions, however, indicate that temperature increases overwhelm the signals in precipitation, such that uncertainties in future precipitation patterns have little impact on projected fire trajectories (Girardin and Mudelsee, 2008; Bergeron et al., 2010).

5. Management implications and options

Management of forests and fire suppression efforts in eastern boreal Canada, particularly in the province of Quebec, have been deployed at a time when fire danger and activity were potentially at their lowest levels on the Holocene scale. Knowledge, understanding and experiences of fires by the public, communities and forest management sectors may hence be significantly underestimated. The vast majority of all areas burned is due to escaped fires, and those that grow to high intensities are costly and difficult to suppress (Podur and Wotton, 2010). Even with increased investments in fire suppression capacity, about 3–4% of fires would still escape (McAlpine and Hirsch, 1999; Podur and Martell, 2009). Fire suppression agencies can be expected to be increasingly overwhelmed as climatic change creates fire danger conditions similar to those experienced during the pre-industrial era, leading to higher numbers of escaped and intense fires (e.g. Podur and Wotton, 2010). A rise in fire activity to levels experienced during the pre-industrial era (i.e. a twofold increase in the annual proportion of burned area; Fig. 8) will have strong implications for managers as harvesting practices will be increasingly competing with fire activity. The extent to which managers will be able to replace fire by clear cuts (combined with site preparation) in the ecosystem-based approach will be even more limited than it is currently, due to the predicted increase in fire activity. Nevertheless, the upper-bound limit of the historical fire activity is not expected to be reached in the next few years (Girardin and Mudelsee, 2008). Hence, there is time for preparedness and for exploring new management strategies that will ensure the sustainability of forest management under a changing climate (Le Goff et al., 2005). Here, we briefly review adaptation options covering the strategic and silvicultural aspects of forest management.

The maintenance of diverse forest compositions and age class distributions will be a key element for maintaining forest resilience in this boreal system. In spite of significant changes in fire activity on the Holocene scale, evidence from pollen-based analyses suggests that the vegetation remained relatively stable in terms of species present, but variable in their relative importance (Carcaillet et al., 2010; Genries et al., in press). Additionally, some other evidence indicates that the proportion of old forests (age > 100 years) in forested landscapes has always been important, in spite of the significant variations in fire activity (Cyr et al., 2005; Simard et al., 2007). These two elements contributed to the high resilience of the eastern boreal forests to past variations in fire activity. Harvesting practices that maintain these attributes should be explored to guarantee the sustainability of forest management. Notably, harvest practices that allow the maintenance of a forest cover, like some variable retention cuts, may be a good solution. The use of partial cuts will limit the opening of the forest cover created by harvesting. Development of alternative silvicultural interventions that would emulate secondary disturbances (e.g. wind, insects) rather than fire would be necessary to maintain pre-industrial forest characteristics (e.g. composition and age class distribution).

While fire is the main driver of the boreal forest dynamics, the risk that it poses to forest productivity estimates that feed into timber supply models is not always taken into account during the planning phase; it is a posterior process via replanning (Savage et al., 2011) and salvage logging (Nappi et al., 2004). Current timber supply planning tools are fundamentally deterministic and ill-adapted to deal with stochastic events such as fires. However, research efforts have been deployed over the last few decades specifically to deal with such integration of disturbance risks (e.g. van Wagner, 1983). Timber supply models accounting for the effect of fire on timber supply invariably lower the timber supply to stabilize it in the face of future fire risk (van Wagner, 1983; Armstrong, 2004; Peter and Nelson, 2005; Savage et al., 2011). This timber supply reduction constitutes an insurance strategy against the fire risk (Savage et al., 2011). The decrease in timber estimates that should be granted may be modulated across forest areas according to different factors, including the local fire activity and forest productivity.

Fire smart management aims at reducing area burned through the manipulation of forest stand structure and composition. Because deciduous stands are characterized by lower flammability than coniferous stands (Hély et al., 2001), these could be used as strategic barriers combined with pre-existing fire breaks (roads, lakes and rivers) to decrease the landscape's susceptibility to fire. Prescribed burning, which consists of fire intentionally ignited with specific goals, can be used to alter fuel structure and composition (fuel load, fuel continuity, or stand age distribution across a landscape). A drier climate might facilitate the use of prescribed burning at lower intensities in the future, although fire agencies may be reluctant to use such a tool when fire conditions are harsh. Another option resides in manipulative vegetation treatments. This approach was initially developed to protect timber reserves against high fire risks in the boreal forest of Alberta, where forests have a strong deciduous component (Hirsch et al., 2004; Krawchuk and Cumming, 2011). These treatments can become a reasonable option under increasing fire danger conditions. However, optimal conditions for manipulative vegetation treatments are not necessarily met in the northern managed forests of eastern Canada. Assessing the capacity of the forests to support such high deciduous components, particularly in the context that future climates may be unsuitable for the viability of some tree species, is therefore essential.

Other options directly reside in the logging practices. To mitigate losses of wood volumes due to fire, Jayen et al. (2006) recommended the use of salvage logging in forest areas that underwent moderate burn, where germination beds and seed rain could be insufficient to ensure a good restocking of stands. Severely burned stands, on the other hand, may regenerate spontaneously without any harvesting or silvicultural intervention.

Finally, a sound option for decreasing the exposure of silvicultural investments to an increasing fire danger is to use tree species necessitating a shorter rotation (Lindner et al., 2000; Ogden and Innes, 2007). Either fast-growing species (hybrid poplars) or species adapted to frequent fires, such as *Pinus banksiana* (Lamb.) may become species of choice in this case. Both species correspond to two different (and not mutually exclusive) strategies in the face of frequent fires: either harvest trees before a fire occurs (hybrid poplars) or ensure a good post-fire regeneration (*Pinus banksiana*) minimizing silvicultural efforts to return to a good stand stocking. Nevertheless, it should be kept in mind that some species are associated with higher flammability (e.g. Podur and Martell, 2009), and thus if this type of manipulative strategy is employed, managers should carefully consider the balance between losses under high fire activity and benefits brought on by higher forest stand productivity. The combined use of fast-growing coniferous species along with fine cartography of forest values at risk, fuel management and fire barriers should offset some of the increased risks that might occur with climatic change.

6. Conclusion

By establishing the pre-industrial upper limit of fire activity, and knowing that past changes in fire activity did not alter the forest composition and diversity, our study shows how natural disturbance knowledge can be used as a guideline for forest management. The metadata analysis conducted in the present study provides compelling evidence of a synchronous pattern of decreasing fire activity and fire-conducive climatic conditions in eastern and western areas of Canada during the past century and earlier, reinforcing the idea of climatic control over fire suppression and land-use changes. While this decrease in fire activity has in recent decades given some flexibility to managers to replace fire by forest harvesting, in eastern Canada this flexibility is expected to decrease in upcoming decades: the climate will become drier and future fire activity is predicted to reach the upper bound of the pre-industrial range of variability. Fire suppression capacity will be overwhelmed in the future, but silvicultural practices and timber supply planning may be adapted to the changing fire activity. This ecological knowledge should help to define forest management actions in the context of the implementation of sustainable forest management strategies considering future climate change.

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