Holocene fires in eastern Canada: Towards a forest management perspective in light of future global changes

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Studies on the Holocene fire history in eastern Canada at local and regional scales decipher the relationships between climate and vegetation, which are used to simulate future fire risk.

In eastern boreal Canada, interest in fire-related studies has increased with the emergence of a new forest management paradigm based on the emulation of natural disturbance regimes (e.g., Gauthier et al., 2008). A key need is to improve understanding of the variability of past disturbances and their linkage with climate and ecosystems during the Holocene (11.7-0 ka). Research conducted over the last 15 years has focused on: (i) reconstruction of natural ranges of fire variability (frequency, size, severity), (ii) analysis of fire-climate dynamics, and (iii) modeling of future regimes.

Local reconstructions of fire regimes

Reconstructions of long-term fire regimes in eastern Canada first attempted to document past changes in fire frequency and fire return intervals (FRI), a component deduced from both dendroecological data (e.g., age structure, fire-scars; Bergeron et al., 2004; Bouchard et al., 2008; Le Goff et al., 2008) and sedimentary charcoal data (Carcaillet et al., 2001; Ali et al., 2009). For example, sediments from seven lakes were sampled in the transition region between two vegetation zones; a mixed needleleaf/broadleaf vegetation (dominated by fire-intolerant species) and the northern boreal forest—a closed-crown needleleaf vegetation dominated by fire-prone *Picea mariana* (Black Spruce). Charcoal time series were broken down into background and peak components, providing millennial-scale series of FRI (Carcaillet et al., 2001; Ali et al., 2009). The two vegetation zones yielded different temporal patterns of FRI, with maximum fire frequency between 5.8 to 2.4 cal ka BP in the north, and after 2.5 cal ka BP in the south. These different fire histories from within the same region raised questions about the long-term relationships between fire and climate in explaining vegetation distribution. In the north, the mean FRI during the Holocene indicated a higher fire frequency than in the south, consistent with the observation that the dominant species, Black Spruce, is fire-prone. Additionally,

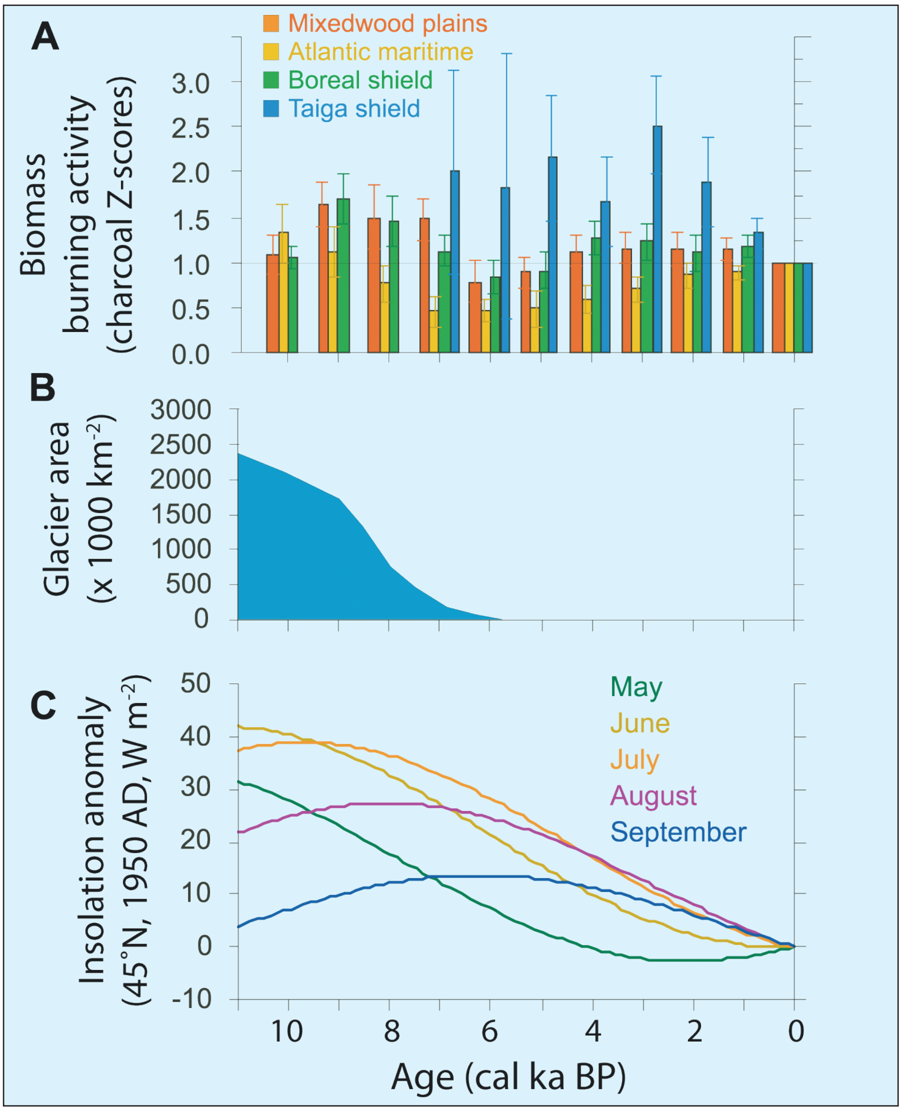

*Figure 1: **A**) Biomass burning activity (z-scores = anomalies calculated to the present-day) assessed from sedimentary charcoal from eastern Canada (modified from Bremond et al. in press). The colors correspond to the Canadian ecozones (SISCan, 2008). **B**) Termination of the Laurentide ice cover inferred from a reconstruction of ice-sheet areas (Dyke et al., 2003). **C**) Insolation computed at 45°N (Berger and Loutre, 1991).*

fires in both zones were synchronous from 8 to 4 cal ka BP, suggesting that the main driver was climate, with longer or drier fire seasons creating large fires (Ali et al., 2009). After 4 cal ka BP, the independence of fire histories among sites suggests that local features controlled fire occurrence. A progressive rise in regional water tables in Ontario and Québec beginning ~4 cal ka BP (e.g., Muller et al., 2003; Moos et al., 2009) may have modified fuel moisture and landscape connectivity and resulted in more small-size fires (Ali et al., 2009). This role of landscape on fire is well illustrated by fire-history studies on islands compared with those from mainland regions (Bergeron, 1991), and by present-day fire modeling (Hély et al., in press).

But how can we define the natural range of fire variability in a changing climate? A key issue is to disentangle natural internal processes that control forest dynamics from external processes, such as those controlled by the climate. Even if natural fire and vegetation histories were perfectly known, past conditions might not be relevant for understanding present and future fire conditions. For example, ice

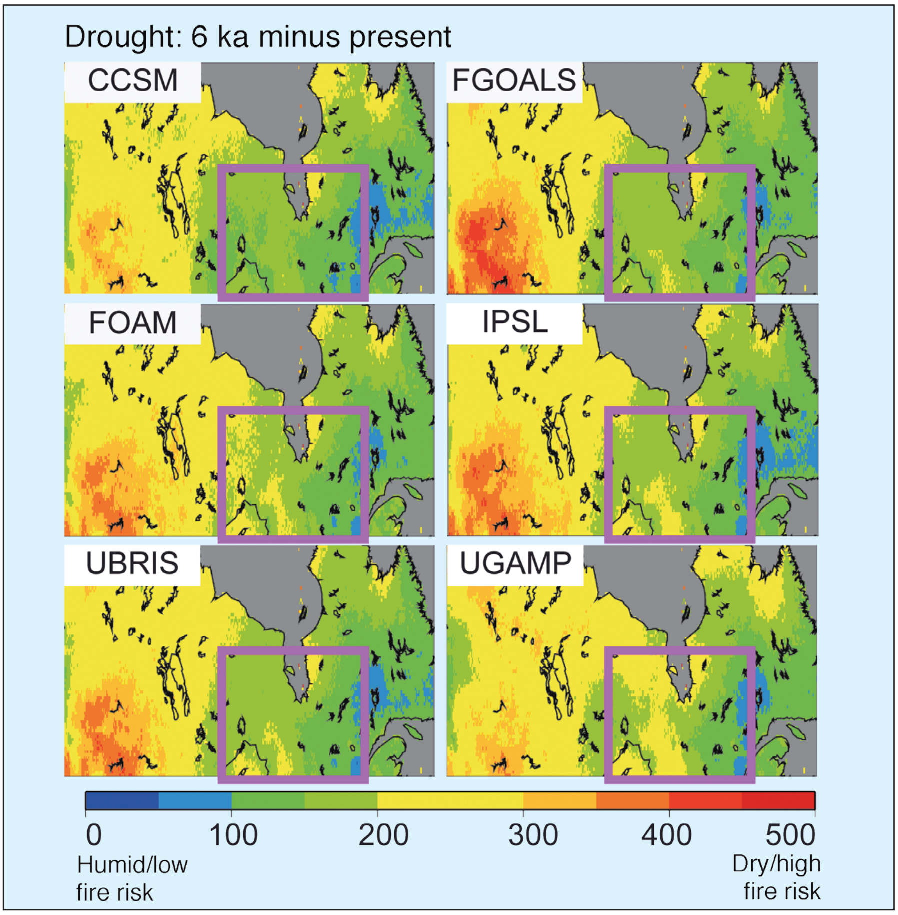

Figure 2: Spatial distribution of the mean Drought Code (DC, unitless). The values are for July at 6 cal ka BP versus present-day conditions simulated by general circulation models (GCMs: CCSM3 (Collins et al., 2006); FGOALS (Yu et al., 2002); FOAM (Jacob et al., 2001); IPSL (Marti et al., 2005); UGAMP (Slingo et al., 1994)). The DC is an indicator of fire danger potential, part of the Canadian Forest Fire Weather Index used to predict the risk of fire ignition based on weather conditions (van Wagner, 1987; De Groot et al., 2007). The GCM simulations were compared based on the mean values for the region in the rectangle (90-70°W and 47-55°N). No significant difference was highlighted among GCMs (one-way ANOVA, F = 1.851, df = 153, p > 0.05).

cover before ~6 cal ka BP in north-central Quebec (Fig. 1) maintained periglacial conditions, whereas climate was warmer than present before 8 cal ka BP in Alaska and northwest Canada (Kaufman et al., 2004).

Sub-continental reconstructions: Fire-vegetation-climate linkages

Sub-continental fire reconstructions have been developed from regional charcoal datasets for eastern Canada (Carcaillet and Richard, 2000; Carcaillet et al., 2002). Based on data downloaded from the Global Charcoal Database (see data information below; Power et al., 2008), Bremond et al. (in press) highlighted the south-north variability of Holocene biomass burning and linked it with the main ecozones and regional climate, which was influenced by both ice cover and insolation (Fig. 1). Biomass burning in the southern ecozones of eastern Canada (Mixedwood Plains, Atlantic Maritime, Boreal Shield East) occurred as soon as the ice sheet collapsed between 10-7 cal ka BP (Fig. 1b), whereas fire activity was lower from 7-5 cal ka BP when climate was drier according to lake-level reconstructions (Hély et al., 2010). Conversely, the moister late Holocene experienced higher fire activity in these southern ecozones. This reconstruction supports evidence of annually colder and drier climate conditions during the early Holocene (Muller et al., 2003; Viau et al., 2006) promoting fires. Annually drier and warmer conditions followed in the middle Holocene with lower fire activity, in contrast with the late Holocene when biomass burned under an annually wetter climate. This pattern suggests that fires activity does not depend on annual precipitation but rather on summer conditions, which were likely wetter on average during the middle Holocene and drier since 4 cal ka BP (Carcaillet and Richard, 2000). The Taiga Shield East (northern forest ecozone) displayed higher-than-present fire activity from 7 to 1 cal ka BP, with fires likely being important sources of carbon emissions during that time (Bremond et al., in press). This reconstruction matches well with data from the adjacent northern boreal forest (Ali et al., 2009) that display a different temporal pattern of fire from that of the southern boreal ecozones. The fire histories thus suggest that the northern Quebec-Labrador Peninsula displayed two fire-climate systems, a northern one under the influence of Arctic air masses, and a southern one under the influence of the Caribbean and the Pacific air masses.

Modeling past and future fires

The ultimate objective of fire-history research is to improve our ability to simulate future fire regimes through numerical models. Several modeling approaches have been used. First, the Fire Weather Index (an estimation of the risk of wildfire) has been simulated under scenarios of 1 x CO_2 and 2 x CO_2 greenhouse gas emissions using outputs from general circulation models (GCMs) in order to provide estimates of present and future fire risks (Flannigan et al., 2001). Second, the Drought Code (DC), an index of moisture content of deep organic matter (e.g., Girardin et al., 2009; Girardin and Wotton, 2009), has been computed using an ensemble of GCMs for 6 ka (Fig. 2), a period considered to have had minimal temporal and regional variability in fire activity. The area south of Hudson Bay (rectangle; Fig. 2) has high-quality and abundant paleodata to test past DC simulations. Multiple-comparison tests showed no difference among the six GCMs (Fig. 2), allowing us to use the UK Universities Global Atmospheric Modelling Program (UGAMP) GCM—the sole GCM providing climate data at each millennium—to simulate the DC over the entire Holocene for eastern Canada (Hély et al., 2010). The seasonal cycle of insolation was important for past fire activity as it modified the fuel dryness necessary for ignition and fire spread. Variations in monthly insolation curves during the Holocene (Fig. 1c) match well with the fire reconstruction and the simulated fire season, both in length and magnitude (Hély et al., 2010). The long-term diminishing trend toward present-day low fire activity in eastern Canada is attributed to the reduction of summer insolation from 6 cal ka BP to present. Predicted changes in temperature and precipitation over the next decades, as a consequence of increasing concentration of atmospheric CO_2, could reverse this downward trend in fire activity. Indeed, estimates suggest that future fire risk will reach values similar to the most severe values of the Holocene (Bergeron et al., in press).

Conclusion

Information on the long-term variability in mean FRI obtained from charcoal-based fire history reconstructions is relevant for sound boreal-forest management. Paleofire records encompass a long history of varying ecological conditions and document the resilience of the boreal forest to changes in disturbance regime. In this context, the cumulative impacts of fire and timber harvesting are worrying. It has already been shown that clear-cut harvesting has considerably altered the age-class representation of forests at the landscape level by diminishing the number of stands older than the length of a typical harvest rotation (Bergeron et al., 2006; Cyr et al., 2009). Excessive use of even-aged management, therefore, erodes ecological resilience by reducing ecosystem variability in time and space (Drever et al., 2006), and this erosion will be exacerbated by the predicted increase in fire with future climate warming (Bergeron et al., in press).

Data

Charcoal data is available from the Global Charcoal Database http://www.bridge.bris.ac.uk/projects/QUEST_IGBP_Global_Palaeofire_WG/index.html

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Fire and climate variation in western North America from fire-scar and tree-ring networks

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Multi-scale fire-scar networks in western North America open new lines of inquiry into fire as an ecosystem process and reveal interactions of top-down and bottom-up regulatory factors across scales of space and time.

Fire regimes (i.e., the pattern, frequency and intensity of fire in a region) reflect a complex interplay of bottom-up and top-down controls (Lertzman et al., 1998; Mc Kenzie et al., in press). Bottom-up controls include local variations in topographic, fuel and weather factors at the time of a burn (e.g., fuel moisture and continuity, ignition density and local wind and humidity patterns). Bottom-up regulation is manifest as fine-scale spatial and temporal heterogeneity in fire behavior and effects within landscapes subject to the same general climate. Examples include variation in fuel consumption, tree mortality and soil effects, which create complex burn severity legacies that can influence subsequent fires (Collins and Stephens, 2008; Scholl and Taylor, 2010).

Climate is the primary top-down control of fire regimes, acting largely through interannual regulation of biomass production, fuel moisture and regional ignition patterns, and control of the geographic distribution of biomes. Top-down regulation leads to spatial and temporal synchrony in fire occurrence beyond scales at which individual fires are likely to spread.

Recent scientific publications and interest in fire climatology on centennial to multimillenial timescales has expanded our understanding of the interplay of bottom-up and top-down regulation of forest fire regimes (Falk et al., 2007; Swetnam

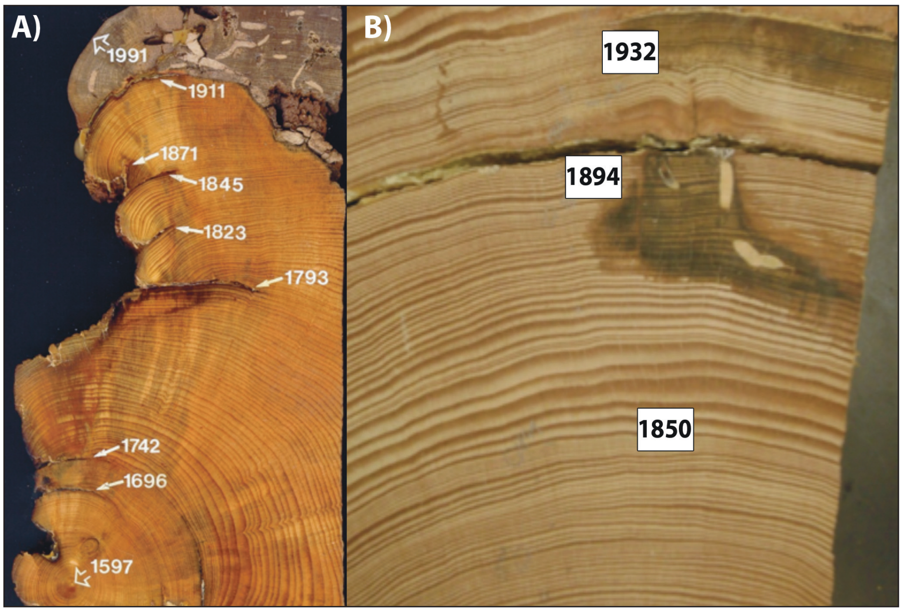

Figure 1: Tree-ring evidence of fires includes cross-dated fire scars and abrupt increases or decreases in ring width. ***A****) Cross-dated* Pinus ponderosa *fire-scarred sample (Photo: P. Brown, Rocky Mountain Tree-Ring Research).* ***B****) Bigcone Douglas-fir (*Pseudotsuga macrocarpa*) sample from Los Padres National Forest, USA, exhibiting growth anomalies following an 1850 wildfire, a buried fire scar dated to an 1894 wildfire, and both a fire scar and growth change from the 1932 Matilija Fire (Photo: K. Lombardo, Laboratory of Tree-Ring Research, University of Arizona).*

and Anderson, 2008; Conedera et al., 2009; Whitlock et al., 2010). New understanding of broad-scale ocean-atmosphere oscillations (e.g., El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO)) and their influence on regional climate, has clarified the mechanisms that synchronize fires across regions (Schoennagel et al., 2005; Kitzberger et al., 2007; Heyerdahl et al., 2008; Trouet et al., 2010).

Contemporary human influences on fire regimes (including fire suppression, forest management, altered landscape configurations and the spread of non-native species) complicate the analysis of what drives fire regimes. Modern data cover a limited time frame and thus cannot capture longer-term variation in fire regimes driven by climate variability and ecosystem succession. Paleoecological data are essential to understand interactions of