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The reconstruction of burned area and fire severity using charcoal from boreal lake sediments

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Abstract

Although lacustrine sedimentary charcoal has long been used to infer paleofires, their quantitative reconstructions require improvements of the calibration of their links with fire regimes (i.e. occurrence, area, and severity) and the taphonomic processes that affect charcoal particles between the production and the deposition in lake sediments. Charcoal particles >150 μm were monitored yearly from 2011 to 2016 using traps submerged in seven head lakes situated in flat-to-rolling boreal forest landscapes in eastern Canada. The burned area was measured, and the above-ground fire severity was assessed using the differentiated normalized burn ratio (dNBR) index, derived from LANDSAT images, and measurements taken within zones radiating 3, 15, and 30 km from the lakes. In order to evaluate potential lag effects in the charcoal record, fire metrics were assessed for the year of recorded charcoal recording (lag 0) and up to 5 years before charcoal deposition (lag 5). A total of 92 variables were generated and sorted using a Random Forest-based methodology. The most explanatory variables for annual charcoal particle presence, expressed as the median surface area, were selected. Results show that, temporally, sedimentary charcoal accurately recorded fire events without a temporal lag; spatially, fires were recorded up to 30 km from the lakes. Selected variables highlighted the importance of burned area and fire severity in explaining lacustrine charcoal. The charcoal influx was thus driven by fire area and severity during the production process. The dispersion process of particles resulted mostly of wind transportation within the regional (<30 km) source area. Overall, charcoal median surface area represents a reliable proxy for reconstructing past burned areas and fire severities.

Keywords
calibration, charcoal, dNBR, fire, forest, lake, severity, taphonomy, trap

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Introduction

In boreal forests, multi-millennial fire regimes and vegetation dynamics, inferred from sedimentary charcoal and pollen respectively, helped to characterize long-term natural range of ecosystem dynamics. This natural range of variability can in turn provide data for improving forest management (Cyr et al., 2009; Hennebelle et al., 2018). Even though large databases are available for reconstructing the fire history for a wide range of ecosystems (Global Charcoal Database, Marlon et al., 2016), many studies have nevertheless highlighted the need for the calibration of charcoal~fire relationships (Aleman et al., 2018; Clark et al., 1996; Hawthorne et al., 2018). Calibration can enable the reconstruction of past fire characteristics on a quantitative basis (Higuera et al., 2011) and improves our understanding of the taphonomic processes affecting the dispersal of charcoal particles, from the production source, via transportation by wind (primary) and water bodies (secondary) and deposition processes, to conservation in natural archives. Charcoal production (in terms of number and surface area of particles) during a fire has been linked to fire characteristics such as burned area, distance from fire, number of fires or fire intensity in a wide range of ecosystems, including grass-dominated ecosystems (Aleman et al., 2013; Duffin et al., 2008; Leys et al., 2015), temperate forests (Adolf et al., 2018; Clark and Royall 1995), boreal forests (Higuera et al., 2011; Ohlson and Tryterud, 2000; Oris et al., 2014) and mountain forests (Adolf et al., 2018; Higuera et al., 2011). Dispersion and deposition of charcoal particles have also been studied using experimental fires in boreal ecosystems, with traps located at the fire edge, within and outside the fire perimeter to a distance of a few tens to hundreds of metres (Clark et al., 1998; Lynch et al., 2004; Ohlson et al., 2011). Sediment traps submerged in lakes

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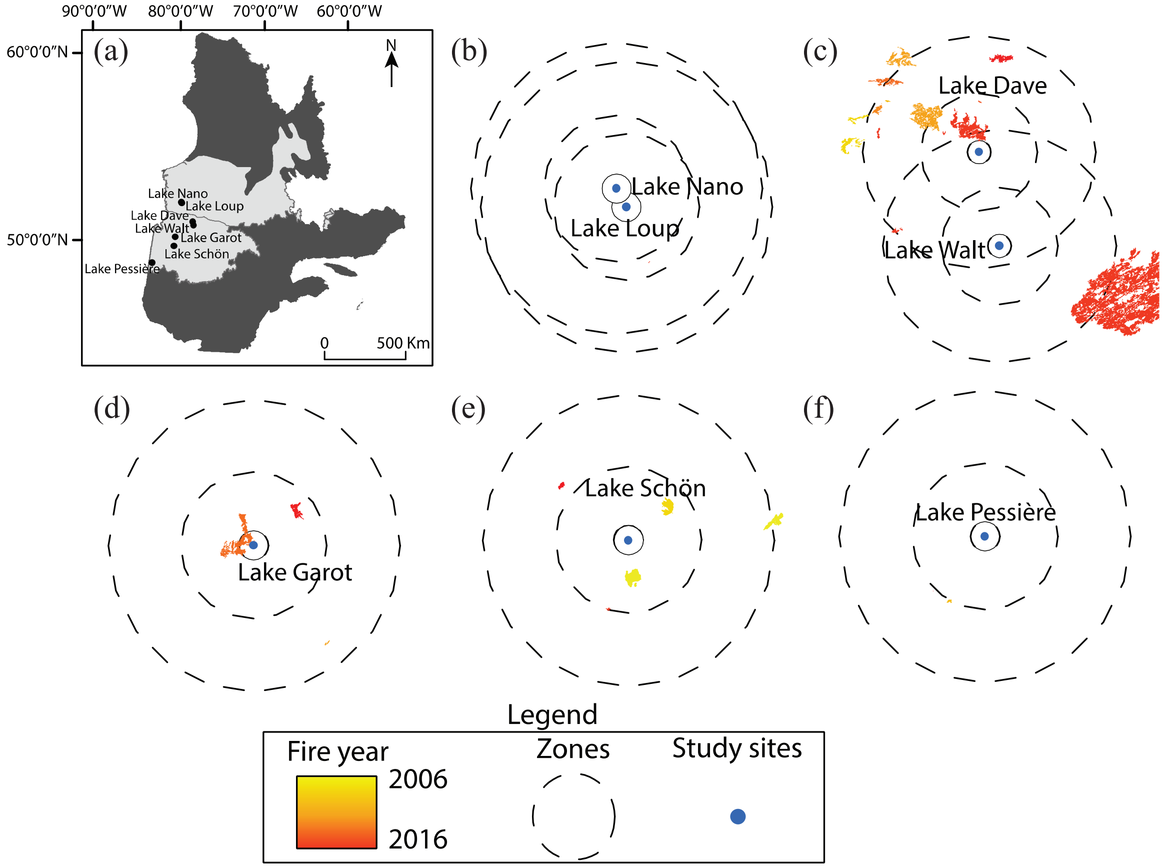

Figure 1. (a) Location of Québec in Canada, (b) Location of the seven study lakes in western boreal Québec forest, Canada, situated between spruce–moss forest (southernmost light gray area) and spruce–lichen woodlands (northernmost light gray area), (c–g) Detail of the three zone radii used (3, 15, and 30 km; dashed circles) and fire location (color gradient) around lakes Nano and Loup (c), Dave and Walt (d), Garot (e), Schön (f) and Pessière (g). The characteristics of the fires recorded ($n = 21$) are presented in Supplemental Table S1, available online. For each lake, fire data were cumulated per year and per zone.

were used to disentangle the potential time lag between charcoal production and deposition in lakes (Oris et al., 2014), while other studies used top-most sediment stratigraphy of charcoal compared to datasets of recent fires for reconstructions of local fire characteristics such as fire dates (Clark, 1990; Higuera et al., 2005; Pitkänen et al., 1999), burned area (Higuera et al., 2011) or fire severity (Higuera et al., 2005). Even though, by definition, fire severity can be referred to as the quantity of above-ground biomass burned (Keeley, 2009), the influence of fire severity at a landscape scale in controlling the charcoal record is still poorly documented (Clark et al., 1996).

Charcoal dispersion occurs primarily in the atmosphere via thermal buoyancy and wind, and has been the subject of theoretical modelling studies (Clark, 1988; Peters and Higuera, 2007). Theoretical models of deposition and incorporation of charcoal into lake sediments have been developed (Higuera et al., 2007) and used to identify peaks of charcoal accumulation that can be attributed to local fire events (Higuera, 2009). This method is widely used to determine past fire occurrences in ecosystems for which the temporal resolution of sediment samples is shorter than the likely fire return interval.

The aim of our study was to identify the most significant fire characteristics that help explain the taphonomic processes involved in charcoal deposition, in particular the variation in charcoal production and airborne transportation that modulates the quantity of charcoal deposited in lakes. The novelty of our approach is the consideration of fire severity at a landscape scale, and the distance between the lake and the source area for the charcoal. We hypothesized that the amount of charcoal deposited at the surface of a lake is directly related to the burned area and fire severity. We therefore: (1) measured the burned area and assessed the severity of fires that occurred around seven head lakes (lakes situated at the head of the catchment area for a river basin) that were monitored for charcoal deposition from 2011 to 2016; and (2) identified the most relevant fire characteristics that helped explain the charcoal influx into the lakes.

Material and methods

Study sites

The seven lakes (Figure 1) are located along a 418-km north–south gradient, and ranged in size from 0.57 ha for Lake Nano to 5.6 ha for Lake Garot (see Supplemental Table S1, available online). All the lakes are situated in the western boreal forest of Québec (east Canada), and are characterized by a relatively short fire cycle of 150 years, as calculated for the last 300 years (Boucher et al., 2011). Five sites (lakes Pessière, Schön, Garot, Walt, and Dave) are located within the spruce–feathermoss bioclimatic domain (Saucier et al., 2009). The lakes surrounding has a vegetation dominated by black spruce (*Picea mariana* [Mill.] BSP) and an understory dominated by feathermoss on clay deposits. Two sites (lakes Loup, and Nano) are located in the spruce–lichen bioclimatic domain (Saucier et al., 2009) on till deposits; the vegetation is dominated by black spruce, except in sandy areas where jack pine (*Pinus banksiana* Lambert) dominates. The climate of the study area has a mean annual temperature of 0.2 ± 3.7°C and annual precipitation of 995 ± 29 mm (snow and rain; Environment Canada, 2011). The water bodies are head lakes or lakes with very limited input, within landscapes that are flat to hilly. Understanding these features is crucial to the quality of the records, because runoff is an important component of the sedimentary charcoal record when the catchment area is large with steep slopes and an extensive stream network (Carcaillet et al., 2007; Earle et al., 1996; Meyer et al., 1992).

Charcoal data

Charcoal traps were placed vertically in the water column in the center part of the lake basin (Supplemental Figure S1, available online), more than 1 m under the water surface (to avoid being disturbed or trapped by winter ice cover), and were emptied annually from 2011 to 2016 (6 years) for lakes Nano, Garot, Pessière, Schön, and Loup, and from 2011 to 2014 (4 years) for lakes Dave and Walt, resulting in 36 charcoal-years. Data acquired between 2011 and 2013 have already been published (Oris et al., 2014) and are available via the Global Modern Charcoal Database (GMCD; Hawthorne et al., 2018). Over the entire study period, we only considered those records taken during years when fires burned within the 30-km zones, resulting in 12 charcoal samples for analysis.

Traps contents were sieved using a 150 µm mesh, which is a size cut-off generally used in the literature, to retain charcoal particles associated with what were assumed to be mainly local fires (Carcaillet et al., 2001; Clark and Royall, 1995; Lynch et al., 2004, Vachula and Richter, 2018) but also some regional fires (Earle et al., 1996; Oris et al., 2014). In this study we also choose a 150 µm mesh to be consistent with Oris et al. (2014) and the recommended size fraction for the GMCD (Hawthorne et al., 2018). The sieved content was soaked in a 5% NaOH solution to deflocculate the particles, and then soaked in a 10% solution of NaOCl to bleach any uncharred organic particles. The charcoal particles were analyzed under a stereomicroscope coupled with a digital camera, and image analysis software (WinSEEDLE 2016a, Regent Instruments Inc., Canada) was used to measure the surface area of the charcoal and the number of particles per sample. These two charcoal metrics are commonly used for paleofire analysis (Leys et al., 2013; Power et al., 2008). In order to analyze the charcoal particle size distribution, which is an important parameter for inferring fire characteristics (Asselin and Payette, 2005; Clark et al., 1998; Oris et al., 2014), we calculated their median surface area.

Fire characteristics

Six fires characteristics were considered around each studied lake: burned area, year of ignition, time lag, charcoal source (zone), severity, and fire-lake distance (Supplemental Table S1, available online). The burned area and date of ignition were extracted from open data shapefiles compiled by the Ministry of Forest, Wildlife and Parks of Québec (https://www.donneesquebec.ca/recherche/fr/dataset/feux-de-foret; Supplemental Table S1, available online). Some fire polygons delineating burned areas encompassed water bodies such as lakes or rivers, leading to an overestimation of this metric. To remove water bodies from fire polygons and LANDSAT images before calculating burned area and fire severity, we used hydrologic data from the National Topologic Data Base (NTDB; www.rncan.gc.ca/sciences-terre/geographie/information-topographique/donnees-gratuites-geogratis/repertoire-telechargement-documentation/17293).

In order to consider the effect of distance between the fires (charcoal source) and lakes (charcoal sink), we used three zones, that is, radii of 3, 15, and 30 km around the lakes (Figure 1). Fires can encompass several zones thus leading to the 30 lines in Supplemental Table S1, available online. We assumed that the 3-km radius would represent a 'local' source of charcoal particles and was selected to encompass the local source area defined in several studies (<1 km (Clark, 1988; Leys et al., 2015; Lynch et al., 2004) and possibly <2 km (Leys et al., 2017)). We selected a 30 km radius as the regional source area of charcoals. In our context we assumed this radius to be a good approximation of the maximal distance charcoal generally travel during boreal forest type fires (Clark, 1988; Oris et al., 2014). We defined an intermediate 15-km radius as the 'semi-local' or intermediate source area. Several studies have provided evidence of a lagged (protracted) charcoal deposition after a fire of up to 5 years (Oris et al., 2014; Whitlock and Millspaugh, 1996). Consequently, we decided to consider that one fire can contribute to a charcoal deposition in the traps if it happened 5 years or less before the charcoal measurement, that is, from 2006 (Supplemental Table S1, available online).

The effect of fire severity on above-ground biomass can be measured either in the field using the composite burn index (CBI; Boucher et al., 2017; Key and Benson, 2006) or via remote sensing data using the differentiated normalized burn ratio index (dNBR; Lentile et al., 2006). Because CBI and dNBR are highly correlated (Cocke et al., 2005), we used the dNBR to infer fire severity at a landscape scale. This index uses spectral bands 4 and 7 of LANDSAT images (30-m resolution). These two bands represent two contrasting responses to burning. Band 4 represents a positive outcome after burning (Key and Benson, 2006), with near infrared (NIR) wavelengths ranging from 636 to 673 nm indicating vegetation content in the area. Band 7 represents a negative outcome after burning, with short-wave infrared (SWIR) ranging from 2107 to 2294 nm indicating the presence of rocks and mineral deposits (Barsi et al., 2014). The difference between these two bands provides a measure of the quantity of above-ground vegetation (NBR; equation 1) and the difference of NBR before and after the fire provides a measure of the quantity of vegetation consumed during a fire, and thus the aerial severity of the fire (dNBR; equation (2)). The calculation used is:

$$\mathrm{NBR} = \left(\mathrm{NIR} - \mathrm{SWIR}\right) / \left(\mathrm{NIR} + \mathrm{SWIR}\right) \tag{1}$$

$$\mathrm{dNBR} = \mathrm{NBR}_{\text{before fire}} - \mathrm{NBR}_{\text{after fire}} \tag{2}$$

where NIR (equation (1)) is band 4 near infrared, SWIR (equation (1)) is band 7 short-wave infrared, $\mathrm{NBR}_{\text{before fire}}$ (equation (2)) is the NBR value taken at the latest date before the fire, and $\mathrm{NBR}_{\text{after fire}}$ (equation (2)) is the NBR value 1 year after the fire event. NIR and SWIR were derived from images chosen from open access LANDSAT data either using LANDSAT-7 (available since April 1999) or LANDSAT-8 (available since February 2013). To minimize the effects of differing phenology phases or solar angle, the pre-fire scenes were selected as near as possible in date to the fire event, and the after-fire scenes 1 year after the fire event.

Definition of severity classes

To analyze the influence of fire severity on the charcoal records, we created severity classes based on the distribution of dNBR values across pixels. Usually, dNBR values range between −0.10 and 0.10 in an unburned area and between 0.10 and 1.35 within a burned matrix (Key and Benson, 2006). Three classes of fire severity were therefore created (Figure 2), excluding an unburned area for dNBR that fell between the minimum value measured and −0.10. Low severity was represented by a value range of [−0.10, 0] (Figure 2; yellow); 0 represented the upper limit of the first quartile and corresponded to surface fires that only affected understory plant species. Medium severity was represented by [0, 0.20] (Figure 2; orange); 0.20 represented the upper limit of the second quartile (=median) and corresponded to fires that consumed the leaves of trees and understory vegetation (e.g. shrubs). The severely burned class was represented by dNBR values of 0.20 and above (Figure 2; red), and corresponded to stand-replacing fires that consumed a greater part of the aerial biomass (Ryan, 2002). The dNBR pixel data were classified using these categories and the corresponding surface area of the burned areas within each severity class was measured within the different zones. We also determined the cumulative severity as the sum of the dNBR values derived from a burned area. In order to remove unburned patches, we only considered pixel values above 0 before classification (Figure 2).

Database architecture

The experiment was designed to link the charcoal measured in a lake (charcoal record) with fire severity, size, and remoteness. We created a database containing the seven sites for which we had yearly recorded charcoal data (Figure 3a and b, respectively) for a total of 36 individual charcoal records (forming the number of rows). From these, we selected the 12 samples that were recorded during a year with a known fire. For each sample ($n = 12$), within the three zones (Figure 3c) we calculated three parameters for each fire (Figure 3d), namely cumulative severity (the summed severity of all fire pixels), burned area and a variable that measured the burned area for the three fire severity classes. These variables were used to isolate their relative importance in explaining the charcoal taphonomic processes. Likewise, we included lake surface area to assess the relative importance of the deposition process. Transportation of particles was studied using the distance between the lakes and the fire edge and the fire locations across the three zones (with radii of 3, 15, 30 km) within which the fire characteristics were assessed.

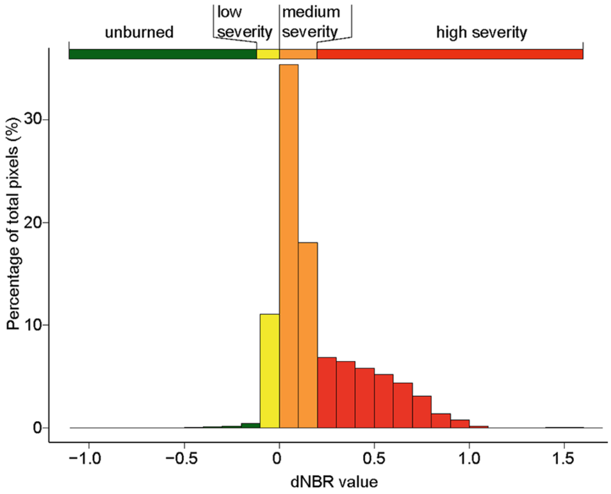

Figure 2. Distribution of dNBR values observed at the study sites; green, unburned pixels (dNBR values of −0.1 and below); yellow, low severity (dNBR values ranging from −0.1 to 0); orange, medium severity (dNBR values ranging from 0 to 0.2); red, high severity (dNBR values of 0.2 and above).

We summed the fire characteristics of the fire the year when the charcoal was recorded for lag $= 0$. Lag $= 1$ corresponds to fire events that can contribute to a charcoal record from zero to one year after it happened and repeated the process up to lag $= 5$. It resulted in 36 variables for the burned area and cumulative fire severity (six lag periods within the three zones), and 54 variables for the burned area for each fire severity class (three severity classes for six lag periods within the three zones), the distance between the burned area edge and the lake and the size of the lake. Overall, the database comprised 92 explanatory variables.

Selection of explanatory variables

The fire variables contained a plethora of zeros, as a result of dichotomies within the different criteria used and the relatively low sample size (charcoal-record years; $n << p$). A Pearson correlation test revealed high correlations between variables (not reported here). Thus, we applied a methodology developed by Genuer et al. (2010) using random forest theory (Breiman et al., 2001) to the charcoal area, charcoal number, and charcoal median surface area data separately. The procedure entailed creating a classification and regression tree (CART) for the

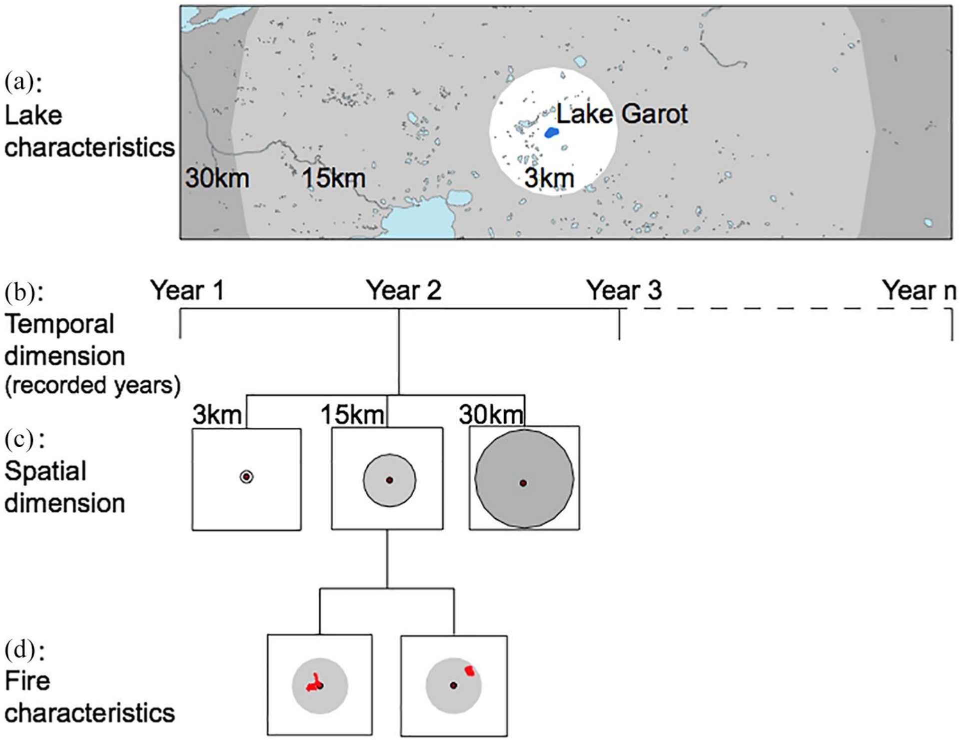

Figure 3. Experimental design used to analyze the effect of various taphonomic processes on charcoal production (fire characteristics), transportation, and deposition-redeposition (lag-time) for the seven study lakes (a). The timing of deposition was assessed using fire characteristics measured up to 5 years before charcoal was recorded in a lake (b). The spatial dimension of charcoal transportation was assessed using three zones, with radii of 3, 15, and 30 km (c), within which the burned area and the fire severity were assessed for each fire (d).

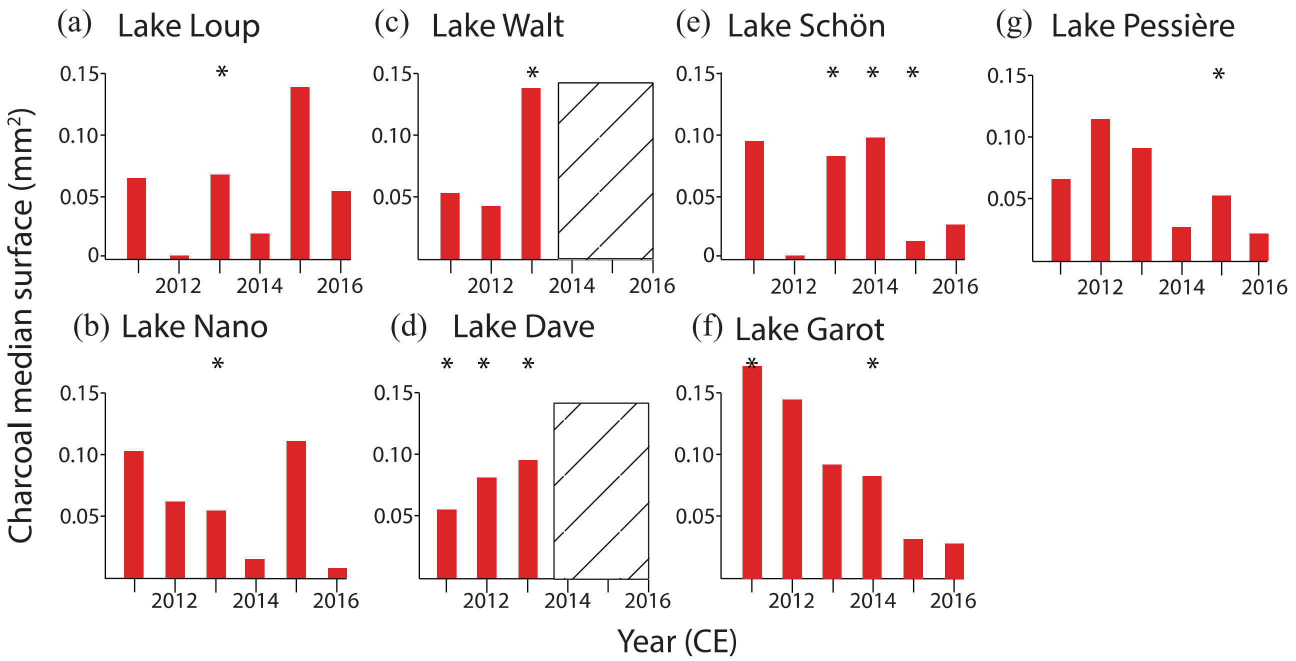

Figure 4. (a-f) Charcoal median surface area for each site and for each year with records. Hatched boxes refer to years for which we do not have charcoal records. The asterisk corresponds to the charcoal records used for the linear regressions.

complete dataset and then extracting increment of mean square error (IncMSE) values. IncMSE values describe the tree misclassification rate for a variable applied to a subset of samples excluded from the tree building by bootstrap resampling, the out-of-bag technique (OOB). The values for the variables were permuted randomly. The mean difference between the OOB-error of a particular variable and the OOB-error calculated from 50 tree building procedures is referred to as the variable importance index (VI).

We also used a complementary method (Genuer et al., 2015) to a pool of variables to identify those with a significant effect on charcoal metrics. Calculations were carried out using package VSURF (Genuer et al., 2015) in R 3.3.2 (R Core Team 2018). Two methods can be used for interpretation or prediction of charcoal measurements, and both were used here. The variable retained in the interpretation pool can include some redundancies such that the second pool used for prediction is a subset of the first pool. For both methods, the variables were ranked based on the standard deviation (SD) of VI. A variable that is poorly linked to charcoal measurements will tend to have a lower VI SD. The minimum VI SD-value was set to define an interpretation threshold, to discriminate between explanatory and less explanatory variables for charcoal measurements. For the interpretation protocol, the first variable in the ranking was used to build a tree, and the OOB-error was then calculated. The remaining variables were added iteratively to build other trees for which the OOB-error was calculated, until the OOB-error stopped diminishing. The variables were then selected until the OOB-error reached its smallest value. The second model used to define the prediction threshold was based on the previous pool of selected variables and used the same method except that a variable was only added to the tree if the OOB-error decreased by more than the threshold value. This threshold value was calculated as the average variation of OOB-error when a noisy variable was added.

Linear regression on predictive variables

Linear regressions were performed on charcoal median surface area records using the pool of variables that were above the prediction threshold. The objective was to analyze the effect of predictors on charcoal accumulation. For each model, the r^2, P, and Akaike Information Criterion (AIC; Akaike, 1974) values were calculated to assess model performance.

Results

Modern fires around the study lakes

For the period 2006–2016, 24 fires occurred within the widest zone (30 km) around the seven lakes (Figure 1, Supplemental Tables S1 and S2, available online). All fire events occurred between 24 May and 16 July; 21 of the 24 were caused by lightning, and the last three fires were of anthropogenic origin. Two fires were limited to the 3-km zone for lakes Garot and Dave, while nine fires were within the 15-km zone for lakes Pessière, Schön, Garot, and Dave, and 19 fires were within the 30-km zone of all seven lakes, with some encompassing several zones around one or more lakes. The accumulated burned area per lake within the 30-km zone was on average 812 ha. The smallest fire had a total burned area of only 1 ha, occurring near Lake Pessière in 2015, while the largest fire was 115,414 ha (5052 ha within the 30-km zone), occurring near Lake Walt in 2013. Fires that affected the lake surroundings were generally of medium to high severity (Figure 2). The lowest fire severity, with a dNBR of −0.32, occurred in 2007 near Lake Dave, representing a surface fire that had a low impact on the aerial biomass and was indistinguishable from the unburned area (Figure 2). The highest fire severity (dNBR of 0.66) occurred in 2011 near Lake Garot and was a crown fire.

Recorded charcoal

For the period 2011–2016, the average (±SD) charcoal median surface area was 0.0714 ± 0.042 mm^2 (n = 36). The smallest value was 0.00808 mm^2, found in Lake Nano (Figure 4b) in 2016, while the highest value was 0.17 mm^2, found in Lake Garot (Figure 4f) in 2011. Overall, the year with the smallest charcoal median surface area was 2016, with 0.0286 mm^2, and the year with the highest value was 2013, with 0.0895 mm^2.

For the recorded years, from 2011 to 2016, charcoal number varied from 0 for Loup (a) and Schön (e) in 2012 to 65 particles for Nano (b) in 2013 with a mean of 7.6 ± 13.7 particles and

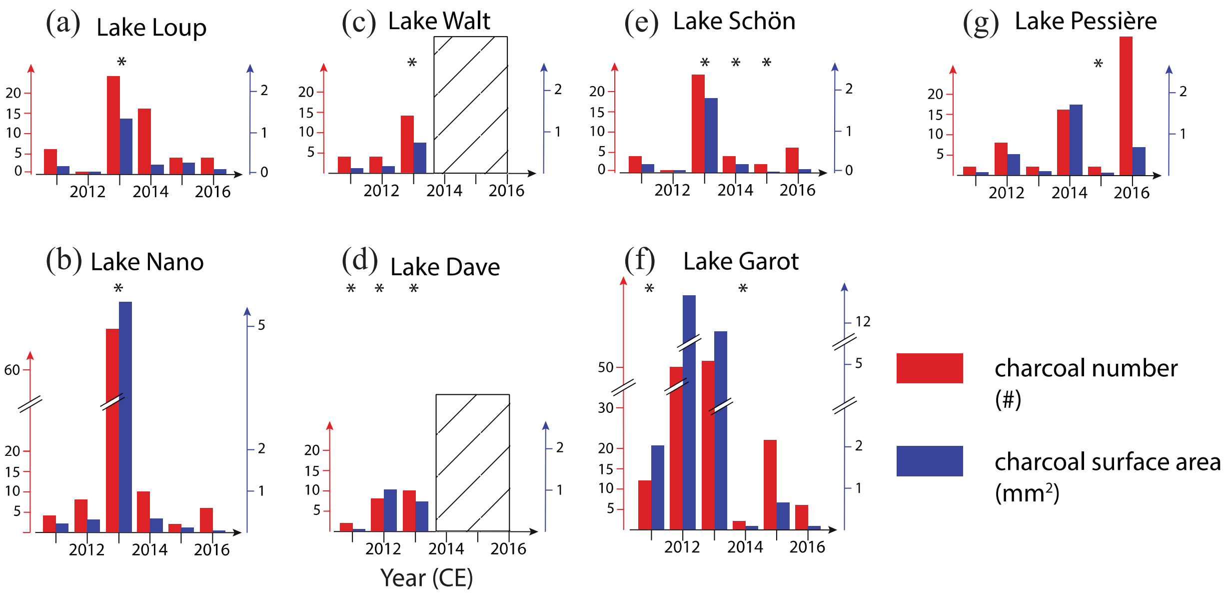

Figure 5. Distribution of charcoal number (red) and charcoal surface (blue) for each site and for every recorded year. The asterisk corresponds to the charcoal records used for the linear regressions.

charcoal surface varied from 0 Loup (a) and Schön (e) in 2012 to 12.8 mm^2 obtained by Garot (f) in 2012 with a mean of 1 ± 2.4 mm^2 (Figure 5). On average, 2011 is the year with the less charcoal number and surface recorded and 2013 is the year with the most important values for both charcoal measurements ($n = 36$).

Interpretation and prediction variables selected based on VI

The most significant variables explaining charcoal median surface area were fire characteristics within the 30-km zone (seven variables), and fire characteristics in the 15-km zone (three variables; Figure 6). Four out of the 10 variables represented a lag interval of 0 year, two variables represented a lag of 1 year and four represented a lag of 2 years. All three categories of fire characteristics measured presented in Figure 6 were among the predictive pool of variables, and those variables were measured within the 30-km zone with a lag interval of 0. Considering the variables above the prediction threshold, variable selection for charcoal median surface area shared two variables with the selection for charcoal surface area (see Supplemental Figure S2, available online), namely ‘medium severity area 30-0’ and ‘total burn area 30-0’. The latter variable also fell within the selection for charcoal surface area. Lake surface area fell within the two most significant and predictive variables for charcoal surface area and number (Supplemental Figure S2, available online).

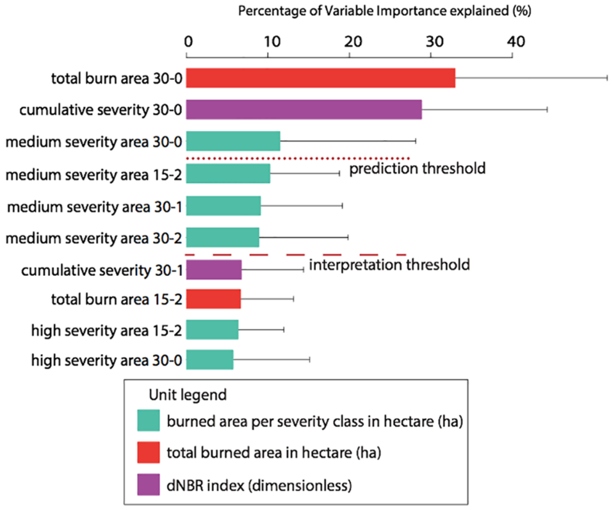

Figure 6. The 10 first explanatory variables for charcoal median surface area. Colors refer to the categories of environmental variables linked to the charcoal: cumulative fire severity (purple), burned area per fire severity class (green), and total burned area (red). Dotted lines refer to the prediction threshold and dashed lines refer to the interpretation threshold. The naming convention for the variable code is: first the type of variable, then the zone in which it was measured and the delay (lag) interval between the fire trait measurements and the charcoal record.

Linear regressions linking charcoal median surface area (CHARms) to fire severity and burned area

We estimated the parameters of the linear regressions linking charcoal median surface area to each variable above the prediction threshold (Figure 6) but tests showed significant parameters only for cumulative fire severity and burned area measured within the 30-km zone with no time lag between the fire event and the charcoal record (Figure 7). When applied to the variable ‘medium severity area 30-0’, the model characteristics ($r^2 = 0.01$, $p = 0.71$, and AIC = 62.1) revealed an inaccurate model.

The model for cumulative severity was significant ($r^2 = 0.35$, $p = 0.041$, AIC = 59.4), and for burned area marginally significant ($r^2 = 0.26$, $p = 0.088$, AIC = 60). The resulting equations for these 30-km radius models are:

$$Cumulative\ severity = \exp\left(41.75CHAR_{ms} + 0.82\right) - 1 \quad (3)$$

$$Burned\ area = \exp\left(34.57CHAR_{ms} + 1.51\right) - 1 \quad (4)$$

where exp(x) refers to the natural exponential function.

Discussion

The results show that the median surface area of charcoal particles in boreal forest is explained by cumulative fire severity and burned area within a 30-km zone during the year (with no time lag), while charcoal number and total surface area are mostly

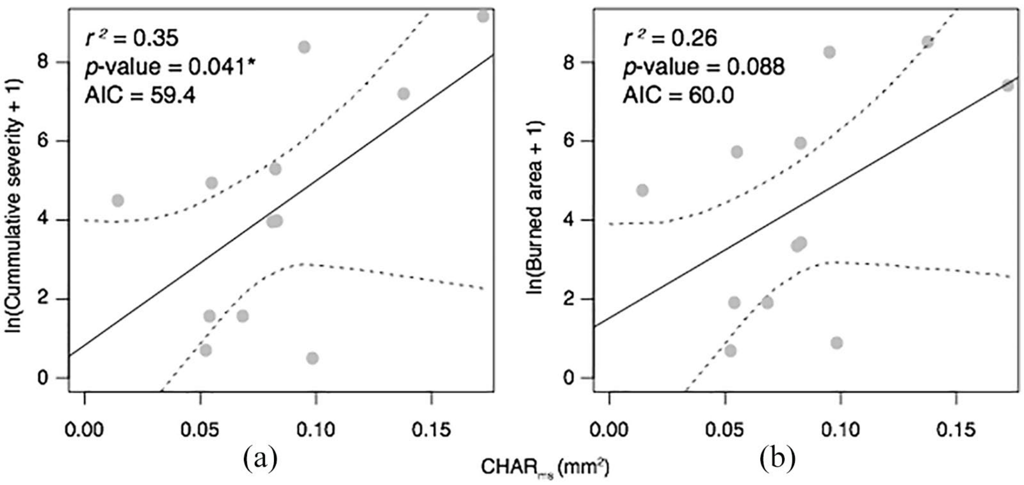

Figure 7. Linear regression between charcoal median surface area from the 12 charcoal records (CHAR$_{ms}$) and (a) cumulative severity measured within the 30-km zone with no time lag between the fire and charcoal measurement, and (b) linear regression between burned area in the 30-km zone with no time lag and charcoal median surface area. Dotted lines correspond to 95% confidence intervals obtained with bootstrap resampling (1000 iterations).

influenced by both lake surface area and medium fire severity (30-km zone, no time lag, Supplemental Figure S2, available online). It appears that taphonomic processes involving charcoal production during a fire, that is, area, severity, and transportation by wind (30 km), are the main drivers influencing the charcoal deposition in boreal lake sediments.

Time-lag between fire and cumulating year affects charcoal deposition

By considering a lag between fires and charcoal measurements, we analyzed the relative influence of primary transportation by buoyancy and wind, and secondary transportation as a result of multiple processes, such as runoff and disturbance caused by wind eddies or biota. The delay between a fire and a charcoal peak can be up to 5 years after the actual fire event (Oris et al., 2014; Whitlock and Millspaugh, 1996), potentially because of wind-caused eddies (Bradbury, 1996), runoff sustaining a flux of charcoal even a few centuries after a fire within a mountain relief landscape with an extensive stream network (Carcaillet et al., 2007), or bioturbation by moose (Bump et al., 2016), beavers or diving ducks foraging in shallow waters (Bakker et al., 2016) that can cause reworking of sediments which has been documented for pollens (Davis, 1973). However, the study lakes were head lakes situated in a flat-to-rolling landscape, thus reducing partially or completely the runoff effect (e.g. Lake Pessière, with a totally flat topography). The size of the selected lakes was too small to support disturbance by eddies, but bioturbation by moose or beaver in shallow waters could still offer a potential explanation for a protracted charcoal record. However, our results suggest that, even if a delay of up to 5 years could eventually happen, charcoal deposition in fact usually occurred during the year of the fire event (lag 0) or the year after (lag 1, Figure 6 and Supplemental Figure S2, available online), which suggests a transportation mode dominated by wind during the fire (a primary process) rather than runoff or bioturbation (secondary processes; Anderson, 2014).

Charcoal source area

One of the first parameter that should impact charcoal source area is lake size. The relative importance of lake surface area in capturing charcoal in the water column was shown in this study (charcoal number and area, see Supplemental Figure S2, available online) echoes the results of studies on surface sediments (Gardner and Whitlock, 2001) and highlights the need to transform data to exclude the effect of lake bodies on charcoal time series (Carcaillet et al., 2002; Power et al., 2008).

Studies have tried to empirically differentiate between local and regional fires using the slope of charcoal size distribution (SCD method) for sedimentary charcoal (Asselin and Payette, 2005; Remy et al., 2018), or charcoal in traps (Oris et al., 2014) from which we used the experimental design to calibrate charcoal-fire relationships with yearly records from traps. Some studies have attempted to linearly link charcoal number with local fire characteristics such as burned area and fire occurrence. No significant relationship has been found within grassland ecosystems (Duffin et al., 2008; Leys et al., 2015), but charcoal number has been shown to be linearly correlated with more regional events (Adolf et al., 2018; Asselin and Payette, 2005). Using the variable classification, we found that no local variables (within the smallest zone) explained the median surface area of charcoal particles but only semi-regional (15-km zone) and regional (30-km zone) scale variables. The distance between the charcoal source and the depositional environment has long been known to explain variation in charcoal samples, through theoretical (Clark, 1988; Higuera et al., 2007), experimental (Clark et al., 1998; Lynch et al., 2004; Ohlson and Tryterud, 2000), and empirical studies (Aleman et al., 2013; Clark and Royall 1995; Duffin et al., 2008). However, in our experimentation, the distance measured between fires and lakes (column 10 Supplemental Table S1, available online) was not a significant variable (Figure 6 and Supplemental Figure S2, available online) which have also been noticed by Oris et al. (2014). The characteristics of boreal forest fires compared with temperate grassland fires (Leys et al., 2017), the landscape physiognomy, or the wind speed might explain these differences. We thus considered in this study that charcoal median surface area of charcoals can be a better indicator of fire severity and burned area than of fire edge-lake distance.

We have therefore shown that in boreal ecosystems characterized by a flat-to-rolling landscape and large and severe fires (Supplemental Figure S3, available online), charcoal particles >150 µm in lakes can originate from long distance transportation over at least 30 km (regional). Under boreal forests conditions, primary transportation of particles during a fire can be greater than 15 km, as shown using a particle dispersion model (Peters and Higuera, 2007) based on equations that simulate the behavior of charcoal deposition (Clark, 1988), or via monitoring experiments (Oris et al., 2014). The charcoal signal indicated by particles on pollen slides can sometimes be related to even more distant fires, the smallest particles (with a minimum of 10 µm) can be occasionally transported above 100 km from the source (Clark and Royall, 1996; MacDonald et al., 1991; Vachula et al., 2018).

The variable selection for median surface area shows some peculiarities compared to charcoal number and charcoal surface area. We decided to use charcoal median surface area since it depends on both charcoal number and surface, thus it is a better representative of charcoal distribution. This metric seems to be less sensitive to lake surface area (Figure 5) but more sensitive to fire severity and burned area (Figures 6 and 7). The later result show that the more a fire is severe and burns a large surface, the bigger the charcoal median surface area will be. This can be attributed to the number of charcoal particles that tends to increase when fire severity or size increases (Duffin et al., 2008; Higuera et al., 2005; Pitkänen et al., 1999). Charcoal particle size is often considered an indicator of proximity (Clark et al., 1998; Higuera et al., 2007) with bigger charcoal particles attributed to local fires. In our case this characteristic didn't seem to be significant since all variables above the interpretation threshold (Supplemental Figure S2, available online) were associated with regional fire characteristics (measured within the 30-km zone). This could be attributed to the small number of local fire, measured within the 3-km zone. But it could also be attributed to the transportation mode, since our methodology mostly allowed us to measure charcoal influx from wind transportation which can prevent charcoal particles from being broken up by secondary transport via water bodies.

Burned area and severity affect charcoal production

Using a non-parametric technique based on random forest theory (Leys et al., 2017), we found that burned area is always among the most significant variables (prediction threshold) in explaining total and median charcoal areas (Figure 6 and Supplemental Figure S2, available online). We also found that fire severity at a landscape scale (30-km radius) is a significant predictor explaining the amplitude of charcoal influx. This observation supports studies that have only measured local fire severity (Higuera et al., 2005). High severity fires can produce more ashes than charred particles, but the high thermal buoyancy above the fire lifts the fragments high above the forest (Clark, 1988; Vachula and Richter, 2018; Val Martin et al., 2010), facilitating the suspension of charred particles in the air and their transportation far outside the region, depending on the wind speed (Clark, 1988). Conversely, low severity fires produce few charred particles relative to burned biomass, and the energy released by the fire front is too low to allow their suspension and thus their transportation away from the burned area (Ohlson and Tryterud, 2000). Studies have only considered burned area or fire occurrence when investigating the role of components on charcoal measurements (Adolf et al., 2018; Leys et al., 2015). The present study thus highlights the importance of fire severity in understanding the charcoal time series (Figures 6 and 7). As the dNBR index refers to the amount of biomass burned (Cocke et al., 2005), it should be considered in subsequent calibration studies. The dNBR index is particularly relevant for methods attempting to distinguish between charcoal peaks in lake sediments generated by surface fires (low severity) and crown fires (high severity).

Quantitative reconstruction of burned area and fire severity using charcoal median surface area

Attempts have been made to reconstruct past fire characteristics using charcoal influx without any consensus on the characteristics being reconstructed, nor experimental verification of the strength of the reconstruction, that is, the burned area (Ali et al., 2012) and fire severity (Colombaroli and Gavin, 2010; Kelly et al., 2013). One statistical relationship correlating fire severity and sedimentary charcoal is based on comparisons between recent sedimentary charcoal in eastern Canada and northeast USA and the Canadian fire severity database of recent fires (Clark et al., 1996). In our study, the linear regressions showed a marginally significant and significant relationship between the median area of charcoal particles and the burned area, respectively, and fire severity. The positive linear regression between ln(*Burned area*) and ln(*Cumulative severity*; Supplemental Figure S3, available online) shows that fire severity (above-ground biomass burned) and burned area are probably linked in boreal ecosystems (Flannigan et al., 2009). Future attempts at quantitative reconstruction of fire regime parameters using transfer functions applied to sedimentary charcoal records would benefit from studies of the relationships highlighted here. The significant linear regressions revealed here could serve as a basis for assessing past fire severity and burned area for paleoecological sites located within boreal forest.

Conclusion

We have demonstrated the importance of considering fire severity at a landscape scale as well as the burned area when calibrating charcoal deposition. This is unsurprising, given that fire severity is strongly linked to the amount of biomass burned during a fire (Boucher et al., 2017); however, until now the relationship between fire severity and charcoal load in sediments has only been demonstrated locally (Higuera et al., 2005). We suggest that subsequent studies should include fire severity in the set of variables used to explain charcoal metrics. We have also shown that the median surface area of charcoal particles is linearly related to the severity of the fire and the burned area. The use of charcoal median surface area allows consideration of charcoal particle distribution and appears to be more independent of lake surface area than number of charcoal particles or total surface area. Applying these transfer functions on long-term sequences will probably enable the reconstruction of past fire severity and burned area as well as fire frequency. These fire characteristics provide more insight into past fire-vegetation history and can help answer complex ecological questions concerning long-term fire-vegetation interactions.

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Supplemental material

Supplemental material for this article is available online.

References

Adolf C, Doyon F, Klimmek F et al. (2018) Validating a continental European charcoal calibration dataset. *The Holocene* 28(10): 1642–1652.

Akaike H (1974) A new look at the statistical model identification. *Transactions on Automatic Control* 19(6): 716–722.

Aleman JC, Blarquez O, Bentaleb I et al. (2013) Tracking land-cover changes with sedimentary charcoal in the Afrotropics. *The Holocene* 23(12): 1853–1862.

Aleman JC, Hennebelle A, Vannière B et al. (2018) Sparking new opportunities for charcoal-based fire history reconstructions. *Fire* 1(1): 1–5.

Ali AA, Blarquez O, Girardin MP et al. (2012) Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. *Proceedings of the National Academy of Sciences of the United States of America* 109(51): 20966–20970.

Anderson NJ (2014) Landscape disturbance and lake response: Temporal and spatial perspectives. *Freshwater Reviews* 7(2): 77–120.

Asselin H and Payette S (2005) Detecting local-scale fire episodes on pollen slides. *Review of Palaeobotany and Palynology* 137(1–2): 31–40.

Bakker ES, Pagès JF, Arthur R et al. (2016) Assessing the role of large herbivores in the structuring and functioning of freshwater and marine angiosperm ecosystems. *Ecography* 39(2): 162–179.

Barsi JA, Lee K, Kvaran G et al. (2014) The spectral response of the Landsat-8 operational land imager. *Remote Sensing* 6(10): 10232–10251.

Boucher Y, Bouchard M, Grondin P et al. (2011) *Le registre des états de référence: intégration des connaissances sur la structure, la composition et la dynamique des paysages forestiers naturels du Québec méridional*. Gouvernement du Québec, Ministère des Forêts, de la Faune et des Parcs, Direction de la recherche forestière, Québec, QC, Mém Rech For No. 161.

Boucher Y, Perrault-Hébert M, Fournier R et al. (2017) Cumulative patterns of logging and fire (1940–2009): Consequences on the structure of the eastern Canadian boreal forest. *Landscape Ecology* 32(2): 361–375.

Bradbury JP (1996) Charcoal deposition and redeposition in Elk Lake, Minnesota, USA. *The Holocene* 6(3): 339–344.

Breiman L (2001) Random forests. *Machine Learning* 45(1): 5–32.

Bump JK, Bergman BG, Schrank AJ et al. (2016) Nutrient release from moose bioturbation in aquatic ecosystems. *Oikos* 126(3): 389–397.

Carcaillet C, Almquist H, Asnong H et al. (2002) Holocene biomass burning and global dynamics of the carbon cycle. *Chemosphere* 49(8): 845–863.

Carcaillet C, Bouvier M, Fréchette B et al. (2001) Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. *The Holocene* 11(4): 467–476.

Carcaillet C, Perroux AS, Genries A et al. (2007) Sedimentary charcoal pattern in a karstic underground lake, Vercors massif, French Alps: Implications for palaeo-fire history. *The Holocene* 17(6): 845–850.

Clark JS (1988) Particle motion and the theory of charcoal analysis: Source area, transport, deposition, and sampling. *Quaternary Research* 30(1): 67–80.

Clark JS (1990) Fire and climate change during the last 750 yr in northwestern Minnesota. *Ecological Monographs* 60(2): 135–159.

Clark JS, Lynch J, Stocks B et al. (1998) Relationships between charcoal particles in air and sediments in west-central Siberia. *The Holocene* 8(1): 19–29.

Clark JS and Royall PD (1995) Particle-size evidence for source areas of charcoal accumulation in late-Holocene sediments of Eastern North American lakes. *Quaternary Research* 43(1): 80–89.

Clark JS and Royall PD (1996) Local and regional sediment charcoal evidence for fire regimes in presettlement north-eastern North America. *Journal of Ecology* 84(3): 365–382.

Clark JS, Stocks BJ and Richard PJH (1996) Climate implication of biomass burning since the 19th century in eastern North America. *Global Change Biology* 2(5): 433–442.

Cocke AE, Fulé PZ and Crouse JE (2005) Comparison of burn severity assessments using Differenced Normalized Burn Ratio and ground data. *International Journal of Wildland Fire* 14(2): 189–198.

Colombaroli D and Gavin DG (2010) Highly episodic fire and erosion regime over the past 2,000 y in the Siskiyou Mountains, Oregon. *Proceedings of the National Academy of Sciences of the United States of America* 107(44): 18909–18914.

Cyr D, Gauthier S, Bergeron Y et al. (2009) Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Frontiers in Ecology and the Environment* 7(10): 519–524.

Davis MB (1973) Redeposition of pollen grains in lake sediment. *Limnology and Oceanography* 18(1): 44–52.

Duffin KI, Gillson L and Willis KJ (2008) Testing the sensitivity of charcoal as an indicator of fire events in savanna environments: quantitative predictions of fire proximity, area and intensity. *The Holocene* 18(2): 279–291.

Earle CJ, Brubacker LB and Anderson PM (1996) Charcoal in north-central Alaskan lake sediments: Relationships to fire and late-Quaternary vegetation history. *Review of Paleobotany and Palynology* 92(1–2): 83–95.

Environment Canada (2011) Canadian climate normals 1971–2000. Available at: https://climate.weather.gc.ca/climate_normals/index_f.html

Flannigan M, Stocks B, Turetsky M et al. (2009) Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology* 15(3): 549–560.

Gardner JJ and Whitlock C (2001) Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *The Holocene* 11(5): 541–549.

Genuer R, Poggi JM and Tuleau-Malot C (2010) Variable selection using random forests. *Pattern Recognition Letters* 31(14): 2225–2236.

Genuer R, Poggi JM and Tuleau-Malot C (2015) VSURF: An R package for variable selection using random forests. *The R Journal* 7(2): 19–33.

Hawthorne D, Mustaphi CJC, Aleman JC et al. (2018) Global Modern Charcoal Database (GMCD): A tool for exploring proxy-fire linkages and spatial patterns of biomass burning. *Quaternary International* 488: 3–17.

Hennebelle A, Grondin P, Aleman JC et al. (2018) Using paleoecology to improve reference conditions for ecosystem-based management in western spruce–moss subdomain of Québec. *Forest Ecology and Management* 430: 157–165.

Higuera PE (2009) CharAnalysis 0.9: Diagnostic and analytical tools for sediment-charcoal analysis. Bozeman, MT: User's Guide, Montana State University.

Higuera PE, Peters ME, Brubaker LB et al. (2007) Understanding the origin and analysis of sediment-charcoal records with a simulation model. *Quaternary Science Reviews* 26(13–14): 1790–1809.

Higuera PE, Sprugel DG and Brubaker LB (2005) Reconstructing fire regimes with charcoal from small-hollow sediments: A calibration with tree-ring records of fire. *The Holocene* 15(2): 238–251.

Higuera PE, Whitlock C and Gage JA (2011) Linking tree-ring and sediment-charcoal records to reconstruct fire occurrence and area burned in subalpine forests of Yellowstone National Park, USA. *The Holocene* 21(2): 327–341.

Keeley JE (2009) Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire* 18(1): 116–126.

Kelly R, Chipman ML, Higuera PE et al. (2013) Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences of the United States of America* 110(32): 13055–13060.

Key CH and Benson NC (2006) Landscape assessment: Sampling and analysis methods. *USDA Forest Service General Technical Report RMRS-GTR-164-CD*: 1–55.

Lentile LB, Holden ZA, Smith AMS et al. (2006) Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire* 15(3): 319–345.

Leys BA, Brewer SC, McConaghy S et al. (2015) Fire history reconstruction in grassland ecosystems: Amount of charcoal reflects local area burned. *Environmental Research Letters* 10(11): 114009.

Leys BA, Carcaillet C, Dezileau L et al. (2013) A comparison of charcoal measurements for reconstruction of Mediterranean paleo-fire frequency in the mountains of Corsica. *Quaternary Research* 79(3): 337–349.

Leys BA, Commerford JL and McLauchlan KK (2017) Reconstructing grassland fire history using sedimentary charcoal: Considering count, size and shape. *PLoS ONE* 12(4): 1–15.

Lynch JA, Clark JS and Stocks BJ (2004) Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: Interpreting fire regimes from charcoal records in boreal forests. *Canadian Journal of Forest Research* 34(8): 1642–1656.

MacDonald GM, Larsen CPS, Szeicz JM et al. (1991) The reconstruction of boreal forest fire history from lake sediments: A comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Reviews* 10(1): 53–71.

Marlon JR, Kelly R, Daniau AL et al. (2016) Reconstructions of biomass burning from sediment-charcoal records to improve data-model comparisons. *Biogeosciences* 13: 3225–3244.

Meyer GA, Wells SG, Balling RC Jr et al. (1992) Response of alluvial systems to fire and climate change in Yellowstone National Park. *Nature* 357(6374): 147–150.

Ohlson M, Brown KJ, Birks HJB et al. (2011) Invasion of Norway spruce diversifies the fire regime in boreal European forests. *Journal of Ecology* 99(2): 395–403.

Ohlson M and Tryterud E (2000) Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10(4): 519–525.

Oris F, Ali AA, Asselin H et al. (2014) Charcoal dispersion and deposition in boreal lakes from 3 years of monitoring: Differences between local and regional fire. *Geophysical Research Letters* 41(19): 6743–6752.

Peters ME and Higuera PE (2007) Quantifying the source area of macroscopic charcoal with a particle dispersal model. *Quaternary Research* 67(2): 304–310.

Pitkänen A, Lethonen H and Huttunen P (1999) Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: Evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. *The Holocene* 9(5): 559–567.

Power MJ, Marlon J, Ortiz N et al. (2008) Changes in fire regimes since the Last Glacial Maximum: An assessment based on a global synthesis and analysis of charcoal data. *Climate Dynamics* 30(7–8): 887–907.

Remy CC, Fouquemberg C, Asselin H et al. (2018) Guidelines for the use and interpretation of paleofire reconstructions based on various archives and proxies. *Quaternary Science Reviews* 193: 312–322.

Ryan KC (2002) Dynamic interactions between forest structure and fire behavior in boreal ecosystems. *Silva Fennica* 36(1): 13–39.

Saucier JP, Robitaille A and Grondin P (2009) Cadre bioclimatique du Québec. *Écologie forestière. Manuel de foresterie*. 2nd éd. Ordre des ingénieurs forestiers du Québec pp. 186–205.

Vachula RS and Richter N (2018) Informing sedimentary charcoal-based fire reconstructions with a kinematic transport model. *The Holocene* 28(1): 173–178.

Vachula RS, Russell JM, Huang Y et al. (2018) Assessing the spatial fidelity of sedimentary charcoal size fractions as fire proxies with a high-resolution sediment record and historical data. *Palaeogeography Palaeoclimatology, Palaeoecology* 508: 166–175.

Val Martin M, Logan JA, Kahn RA et al. (2010) Smoke injection heights from fires in North America: Analysis of 5 years of satellite observations. *Atmospheric Chemistry and Physics* 10(4): 1491–1510.

Whitlock C and Millspaugh SH (1996) Testing the assumptions of fire-history studies: An examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6(1): 7–15.