Long-term decreasing trend in forest fires in northwestern Canada

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Abstract. The annual area of forest burned has decreased in recent centuries over large areas of Fennoscandia, Siberia and temperate North America. To determine if this same trend extends to a sparsely populated region of northern Canada, fire scars on living and dead trees, forest stand ages and charred wood were systematically sampled in 85 study plots in an area of 564 000 km^2 in northwestern Canada. A significant negative trend in the occurrence of forest fires was observed: average area burned per year decreased from 2.0% in the first half of the 19th century to 0.33% in the later half of the 20th century. Annually burned areas correlated significantly with a local tree ring based index, July monthly drought code and the Pacific decadal oscillation but not with June-August mean temperature, distance to the nearest road, or the year of road building. None of the climatic indicators or access history (indicative of the start of local fire suppression) could explain the long-term negative trend in fires. Earlier interpretations that humans dominated the causes of forest fires in the past, even in sparsely populated regions, deserve further attention as a possible explanation for the decreasing trend in fires.

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INTRODUCTION

The ecological literature typically describes the North American boreal forest as a biome that frequently burns in natural lightning ignited forest fires (Rowe and Scotter 1973, Johnson 1992, Payette 1992). Prior to the mid-19th century fire cycles have varied from 30 to 130 years in Canada's boreal forests (Zhang and Chen 2007). However, the majority of fire history studies in North America have been conducted either in the southern part of boreal zone (Weir et al. 2000, Bergeron et al. 2001) or in more temperate coniferous forests (Heinselman 1973, Heyerdahl

et al. 2001). Except for the research based on fire statistics and satellite images spanning the last few decades (Stocks et al. 2002, Kasischke and Turetsky 2006), relatively few large-scale fire history studies (Yarie 1981, Larsen 1997) have been conducted in northern boreal North America or in "the true boreal" as defined by Brandt (2009).

The general view is that climate dictates the area annually burned, at least in remote areas such as the boreal forests of North America. It has been suggested that as a consequence of climatic warming, fires have (and will continue to) become more frequent (Gillett et al. 2004,

Flannigan et al. 2005, Soja et al. 2007), which could be the reason for the increase in the area annually burned seen in the fire statistics. However, the effect of climate on fire frequencies is apparently complex and spatially and temporally variable. Climate change in the 20th century has not led to more high-risk fire weather everywhere in the boreal forests. During the 20th century in southwestern and southeastern Canada, the climate has shifted to conditions less conducive to forest fires, but over the same period, for example, the Eurasian taiga has become drier (Girardin et al. 2009).

Several weather factors, including temperature, precipitation and wind, affect daily fire risk. For example, summer temperature and precipitation together with other climatic variables explained 79% of the annual variation in burned area during the later half of the 20th century in Alaska (Duffy et al. 2005). It has been demonstrated that oscillation of the sea surface temperatures could explain the long-term trends in fire regimes (Kitzberger et al. 2001). In boreal North America, the Pacific Decadal Oscillation (PDO) correlates with forest fires (Duffy et al. 2005, Fauria and Johnson 2008). Another climatic index that has been shown to correlate well with annually burned area is the monthly drought code (MDC) of July in Canada (Girardin et al. 2009).

In addition to climate there are also human factors that have been thought to affect fire regimes. Notably, fire suppression is associated with a decrease in fires in Fennoscandia (Zackrisson 1977) and in North America (Heinselman 1973). However, in northern Canada, forest fires have not been suppressed as effectively or for as long a period of time as in southern Canada or in Fennoscandia. Fires in Canada's remote northern regions were not well documented before the 1950s or 1960s (Stocks et al. 2002) and forest fires which occurred outside of protection zones before about 1980 were neither reported nor suppressed (Simard 1997). Large areas of Canada's boreal forest remain zoned for "modified suppression" by provincial, territorial, and national park agencies, meaning that the forest is allowed to burn unless communities or other infrastructure is at risk (Stocks et al. 2002).

In contrast to recent fire suppression efforts, presumably resulting in a reduction in the areas burned, other human actions may have augmented the occurrence of fires. In the 19th century a common notion was that humans were the predominant cause of forest fires (Blomqvist 1888, Bell 1889). Currently, this is not considered true for most of the boreal North America, as 80% of the burnt area and more than 70% of the number of fires (those >200 ha) in compiled statistics for northern ecozones are caused by lightning-ignited fires (Stocks et al. 2002, Kasischke and Turetsky 2006). Nevertheless, it has been proposed that development activities and industrial forestry have inadvertently promoted lightning fires by increasing the availability of flammable fuels (Arienti et al. 2009, Lindenmayer et al. 2009).

During the last 150 years, forest fires and biomass burning have declined globally (Marlon et al. 2008). This can be clearly seen from fire history field studies in Fennoscandia, southern Canada and the western United States, where annually burned areas have steeply decreased over the last century or longer (Zackrisson 1977, Flannigan et al. 1998, Niklasson and Granström 2000, Zhang and Chen 2007). However, in northern North America the fire history is not clear. While some field studies show lengthening of the fire cycles (Larsen 1997), others point to a considerable temporal variability (Cyr et al. 2009). Indirect reconstructions suggest that there has been no trend over the last three centuries (Girardin and Sauchyn 2008), and compiled fire statistics attest to considerable shortening in fire cycles (Stocks et al. 2002, Kasischke and Turetsky 2006). These ostensible conflicts between studies undoubtedly reflect regional differences, different time horizons over which trends are assessed, and probably some methodological differences. Further field studies are clearly needed to clarify the complex temporal and spatial patterns in the occurrence of forest fires in the northern North America.

The aim of this study is to clarify the fire history of the past two centuries over a large region of northwestern Canada. Specific research questions are: (1) How often have forests burned in the past? (2) Have there been any significant trends in the fire cycle during the last two centuries? (3) What are the causes of any observed temporal patterns in fire cycles?

METHODS

Study area

The study area is located in northeast British Columbia, northwest Alberta, southeast Yukon Territory and southwest Northwest Territories in the Canadian Northwest (Fig. 1). The approximately rectangular study area stretches about 730 km from north to south between latitudes 57°N and 63.5°N, and between 125°W and 111°W longitude. The area encompasses about 564 000 km^2 of which Great Slave Lake and smaller water bodies cover 10%. Topography is mostly flat or gently contoured except for the western margin of the study area. Elevation ranges from 120 m at the Mackenzie River to 2942 m on Mount Sylvia, but mostly varies between 150 and 500 m.

Climate of the region is continental. Average temperature in July is between 15°C and 17°C and in January is between −19°C and −27°C (Environment Canada, National Climate Data and Information Archive 2010). Average annual precipitation is between 280 and 450 mm. The majority of the area belongs to the Taiga Plains ecozone but segments of the Taiga Shield and Boreal Plains ecozones are included in the eastern part of the study area.

Picea mariana (Mill.) Britton, Sterns & Poggenburg, *Picea glauca* (Moench) Voss, *Pinus contorta* Douglas, *Pinus banksiana* Lamb., *Larix laricina* (Du Roi) K. Koch, *Populus tremuloides* Michx. and *Populus balsamifera* L. are the most common tree species. The field layer is typically dominated by dwarf shrubs belonging to genus *Ledum*, *Vaccinium*, and *Empetrum*. The pan-boreal mosses *Pleurozium schreberi* (Brid.) Mitt. and *Hylocomium splendens* (Hedw.) B.S.G. and different species of *Sphagnum* typically cover the forest floor. Based on digital topographic maps from Natural Resources Canada, muskeg and other types of wetlands cover approximately 20% of the study area.

Humans have inhabited northern Canada for thousands of years (Francis et al. 2002). The first humans in the Americas were hunter-gatherers who influenced their environment by hunting large herbivores and by initiating at least some landscape fires. The effect of these early people on forest fire regimes is uncertain but potentially very significant: even a small population of humans, if it wishes to do so, is capable of burning forests more frequently than the forests would naturally burn (Granström and Niklasson 2008). The human population density in the study area is today probably at record high levels, but is still less than 0.1 inhabitants per km^2. There were practically no roads before the 1940s. In the Northwest Territories, the first roads were built in the 1960s. A large portion of the road network was constructed to support the oil, gas and mineral exploration that started in the 1950s and has expanded and continued to the present day. In the southern part of the study area, a modest level of commercial forestry has been practiced in the later half of the 20th century (Schneider 2002). Most of the study area remains unroaded wilderness, dominated by primeval forest and little human use. Fire suppression actions in the area have varied through time and space but the longest policy has been to protect property and lives in proximity to cities, highways and major rivers. Considering our sampling strategy (see Methods: Fire history reconstruction), the road building dates constitute the likely start of fire suppression, although it may have become effective only much later.

Fire history reconstruction

Fire history was reconstructed using (1) fire scars on trees, (2) forest stand ages and (3) fire killed and charred snags in 85 study plots within a buffer zone of 0.2–1.0 km from the existing road network in the area. The first plot was randomly located with ArcGIS software. Additional plots were located with a procedure whereby the next plot was placed on the opposite side of the road 40 km away as the aerial point-to-point distance (Fig. 2). The orthogonal distance of each plot center from the road was randomized using 0.1 km steps to be 0.2–1.0 km. After the first 30 plots the distance from the road was limited to 0.5 km at maximum because of time limitations. The plots were located with the help of a GPS device. If a plot center fell in a water body, it was rejected and a new plot was randomized to be 2–9 km forward along the road on the opposite side of it. The radius of sampling for each circular plot was 100 m, encompassing an area of 3.1 ha. This plot size was considered to be small enough to serve as a point-wise measure of the occurrence of fires, either burnt or not burnt in any fire, while being large enough to have a good chance to
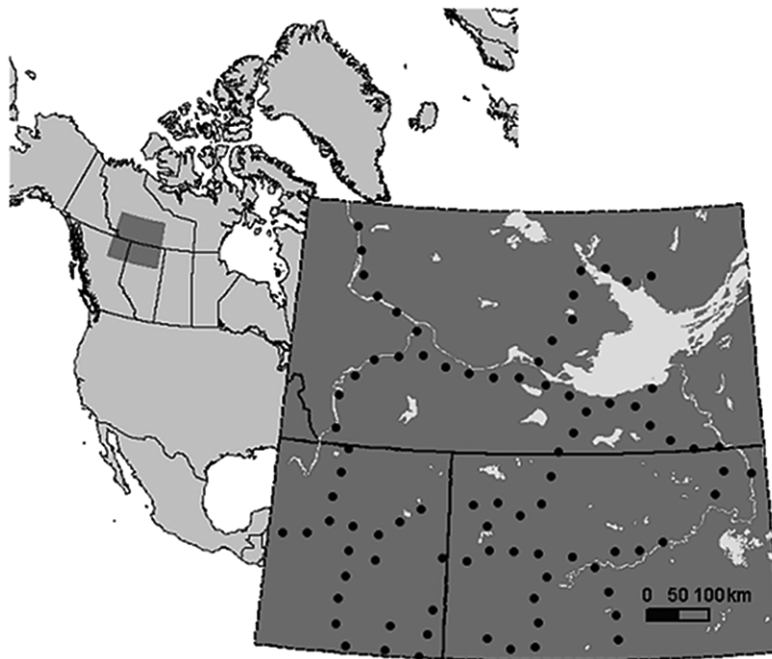
Fig. 1. Locations of the study area and study plots in Northwest Canada.

Rejected plots
moved 2–9 km
forward

90°
orthogonally
from the road

Distance from
the road
0.2 –1.0 km

Distance between plots 40 km
or more

Circular study plots
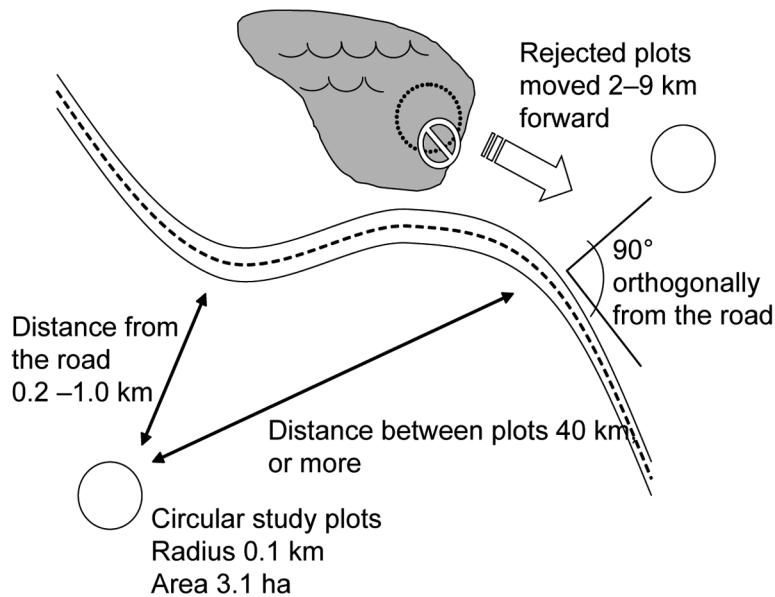Radius 0.1 km
Area 3.1 ha

Fig. 2. Schematic diagram portraying the locating of study plots.

include fire scarred trees. Altogether 453 samples from living trees and 45 samples from dead trees were collected, polished with extra fine sandpaper and brought to the laboratory for analysis by microscope.

Fire scars were used as a primary source because they yield relatively accurate dates for fires. Disks or wedges including fire scars were sawn from up to five living and dead trees per plot. Fire scars are typically located at the base of

the trunk and have a sharply formed injury showing no lesion that grows year after year. The later is typical of scars made by falling trees and fungi. In two plots fire scars were collected more than 100 m from the plot center. However, in both cases fire scars were still considered to have originated from the same fire that had burned the plot center as the forest age and structure were similar in the plot center and at the additionally sampled location further away.

Fire scars from living trees were dated by counting the annual rings backwards from the last year of growth. Possible missing rings can, however, cause an error of a couple of years in dating. This error was minimized by selecting the radius having the broadest annual rings in each sample, and by crosschecking fire scar dates from the same plot. Fire scars from 9 dead trees were dendrochronologically cross-dated (see the later part of this section).

Living trees were sampled for their age in every plot. First, three dominant trees (not growing under the canopy of other trees) nearest to the plot center were sampled. Secondly, one to three trees that subjectively seemed to be the oldest within 20 m from the plot center were sampled. Samples were extracted from as close to the base of the tree as possible, on average less than 0.3 m above the ground level. Ages of the sampled trees were estimated by counting the annual rings to the pith and by adding a fixed number of years to accommodate the time that is needed for open-grown trees to reach the sampled height. Based on our sampling, one year was added to all broadleaved trees, two years to *Pinus* and 5 years to *Picea, Larix* and *Abies*. In a few cases where pith was not present, the missing annual rings were estimated based on curvature of the rings near the pith (Arno and Sneck 1977).

The tree ages were used for inferring fire dates if no fire scars corresponding to the tree ages could be found. Fire was determined to have occurred one year before an estimated year of germination of the oldest sample tree in the plot. To avoid assigning false fires, there had to be at least one other sample tree born within 30 years to indicate a regeneration cohort following a fire. Trees killed and charred by fire were used as additional evidence to ensure that the studied forests were actually burned.

The samples from dead trees were dendrochronologically cross-dated, if possible. Samples from living trees with the longest sequences of undisturbed growth were used to build master chronologies for *Picea glauca* and *Pinus banksiana*. In addition, data provided by H. Fritts, M. Hutton, T. Knowles, C. Larsen, D. Meko, K. Moser, F.H. Schweingruber, C. Stockton and J. Szeicz (World Data Center for Paleoclimatology, International Tree Ring Data Bank 2010) were used for building the master chronologies. Dates for the samples were determined based on a distinctly high correlation with the master series using COFECHA software (Grissino-Mayer 2001) and verified agreement with the known fire years and tree age structure in the plot in question. In all cases, the visual appearance of the sample was also considered to exclude erroneous dates.

Cross-dating proved to be challenging because we were dealing with multiple tree species in a very large area where one master chronology per species is not enough. Of the 45 samples from dead trees only 15 could be dendrochronologically cross-dated. The samples that remained undated were mostly charred snags. Charcoal was found especially on branch tips but not on the trunk, indicating that the tree had probably been killed by the previous fire. Snags that had been dead for a long period before the fire would have very likely been without bark and dry, and therefore would have burned more thoroughly. Hence, the death of trees with charred branch tips was dated to a period immediately (one year) before the last fire in the plot in question.

Very low severity fires that do not kill trees, or even cause scars on them, may not be detected with the methods described above. However, such low-severity fires tend to spread slowly and remain small. The great majority of the area burned in this region is from large powerful fires. The reconstructed fire history was compared with fire statistics, including all documented forest fires, provided by Natural Resources Canada and the fire management agencies of British Columbia, Alberta and Northwest Territories.

Statistical analysis

The average annually burned proportion for a period from year t_0 to year t_1 (including t_1) was estimated as

$$a_{t_0,t_1} = \frac{1}{t_1 - t_0 + 1} \sum_{t=t_0}^{t_1} \frac{b(t)}{c(t)} \qquad (1)$$

where $b(t)$ is the number of burnt plots and $c(t)$ the number of active plots in year t. A plot was determined to be active (i.e., recording fires) since the first determined fire year or since the first year in the annual ring chronology of the plot in question, whichever came first.

The fire cycle for the same period from year t_0 to year t_1 (including t_1) is

$$f_{t_0,t_1} = 1/a_{t_0,t_1} \qquad (2)$$

The fire cycle equals to the time needed to burn a cumulative area equivalent to that of a large reference landscape (on average once by separate, small fires) and it is the inverse of the average of the annually burned proportions (Johnson and Gutsell 1994). The fire cycle also equals the expected point-wise average fire interval.

We assume that in a given year, the study plots behave independently. Then, the number of observed fires for year t follows a binomial distribution, $b_t \sim B(c(t), p(t))$, where $p(t)$ is the probability that a plot burns, given the conditions during the year. When $b(t)$ and $c(t)$ are known, the posterior probability for p_t is the beta distribution Beta($b(t) + 1$, $c(t) - b(t) + 1$). Therefore the 0.025 and 0.975 quantiles of the beta distribution give the 95% confidence interval for $p(t)$.

We used logistic regression to evaluate the effect of several factors on fire occurrence, and the magnitude of a possible residual trend. The dependent variable is the observed yearly number of fires and the covariates are the year, road building date and a set of climatic indicators. The average temperature over June–July–August (JJA), July monthly drought code (MDC), and the annual average Pacific decadal oscillation (PDO) index were evaluated to best explain forest fires in our study area based on earlier research in northern North America (Duffy et al. 2005, Fauria and Johnson 2008, Girardin et al. 2009). We used the annual average PDO value, which is very strongly positively correlated with the January–February ($r = 0.79$), and spring-summer ($r = 0.96$) PDO values used by Duffy et al. (2005) and Fauria and Johnson (2008), respectively. In addition, an index derived from a three-century long reconstruction of tree growth in the Taiga Plains ecoregion by Girardin and Sauchyn (2008) was used as a proxy for climatic forcing on fire regimes in the region. Their reconstruction (hereafter referred to as GiR) is based on the climatically regulated component of variation in tree-ring widths in the region and not directly to burned areas. The GiR index represents an undefined set of weather variables that correlate both with the tree growth and the occurrence of fires.

Historical instrumentally measured PDO indices were acquired from the Royal Netherlands Meteorological Institute Climate Explorer (2010). PDO index values are sea surface temperature (°C) anomalies oscillating around zero; the values used in our analysis ranged from a minimum of −2.3 to a maximum of 3.0°C. July drought codes (MDC; Girardin et al. 2009) for the study area were computed using climate data from the Climate Research Unit of the University of East Anglia and software SimMDC provided by Martin Girardin (Canadian Forest Service, Sault Ste. Marie, Ontario). The historical June-August mean temperatures in Fort Simpson and Hay River during 1895–2008 were acquired from the Royal Netherlands Meteorological Institute Climate Explorer (2010) and the Environment Canada, National Climate Data and Information Archive (2010b). A few missing data entries were assigned an average for the month and station in question.

Road building dates were determined from maps of various dates, other publications (Greenwood 1992), different internet sources, and personal communication with local authorities. Despite these efforts, exact dates could not be found for every road. For these roads the building dates were assigned a midpoint date between a known point of time when the road was not built (for example, from an old map without the road) and when it apparently was present (for example, a more recent map, or the year of field sampling).

We model the hazard of burning $h(t)$ in a year t for plot v by

$$\text{logit}(h(t)) = \alpha + \beta \cdot t + \rho \cdot r_{v,t} + \sum_i \gamma_i \cdot x_i(t) \qquad (3)$$

where $x_i(t)$ are the climatic covariates question, $r_{vt} \in \{0,1\}$ indicates if the road nearest to plot v was built before t, and α, β, ρ, and γ_i are parameters. For clarity, we index the γ_i corresponding to each climatic indicator as γ_{JJA}, γ_{MDC}, γ_{PDO} and γ_{GiR}. The climatic indicators were normalized so that the mean value was 0 and standard deviation 1. Year t was scaled to take values between 0, for the first, and 1, for the last analysed year.

Since we assume that both plots and years are independent of each other, the above model is a straightforward generalized linear model. However, the uncertainty in the dating of the fires is significant, probably varies in time, and differs between the fires dated from stand age (age-dated) and fires dendrochronologically cross-dated from fire scars (scar-dated). We therefore used a Bayesian framework for the regression modeling, which allows incorporating the dating error, which is not exactly known, directly in the analysis. We assume the actual date of a fire recorded for year t is distributed according to a normal distribution $N(t + d_j, \sigma_j(t)^2)$, where $j = a$ and $j = s$, for age-dated and scar-dated fires, respectively. We model σ_a by

$$\sigma_a(t) = (k_1(t - t_0) + k_0(t_1 - t))/(t_1 - t_0) \quad (4)$$

where t_0 and t_1 are the first and the last years in the data, respectively, and k_0 and k_1 are parameters. The systematic error d_j, as well as $\sigma_{s,} = k_2$ are assumed to be independent of t and we assume that $\sigma_a = 0$.

To calculate the likelihood of the observed numbers of each type of fire observation, we also need to know the probability $s(t)$ of the fire being observed only as an age-dated fire. We assume that this nuisance parameter is a function of time since the fire in question, and estimate it by

$$s(t) = \tilde{m}_a(t)/(\tilde{m}_a(t) + \tilde{m}_s(t)) \quad (5)$$

where $s(t)$ is the probability that a fire at year t is observed only as age-dated, and $\tilde{m}_a(t)$ and $\tilde{m}_s(t)$ are kernel-smoothed yearly numbers of observed age-dated and scar-dated fires, respectively.

Now the complete model for the probability of recording a fire on a plot v at year t is

$$h_{a,v}(t) = s(t) \sum_{t'=t_0}^{t_1} N(t + d_a, \sigma_a(t)^2)(t') \, \text{logit}^{-1}$$

$$(\alpha + \beta \cdot t' + \rho \cdot r_{v,t} + \sum_i \gamma_i \cdot x_i(t')) \quad (6)$$

for the age-dated fires, and

$$h_{s,v}(t) = (1 - s(t)) \sum_{t'=t_0}^{t_1} N(t + d_s, \sigma_s(t)^2)(t') \, \text{logit}^{-1}$$

$$(\alpha + \beta \cdot t' + \rho \cdot r_{v,t} + \sum_i \gamma_i \cdot x_i(t')) \quad (7)$$

for the scar-dated fires.

Finally, the likelihood function is given by

$$L = \prod_{t,v} q_v(t)(g_{a,v}(t) \cdot h_{a,v}(t) + (1 - g_{a,v}(t)) \cdot (1 - h_{a,v}(t)))$$

$$\cdot \prod_{t,v} q_v(t)(g_{s,v}(t) \cdot h_{s,v}(t) + (1 - g_{s,v}(t)) \cdot (1 - h_{s,v}(t)))$$

$$(8)$$

where $q_v(t)$ is an indicator function of whether plot v is active in year t, and $g_{a,v}(t)$ and $g_{s,v}(t)$ indicate if an age-dated (scar-dated) fire was recorded on plot v in year t.

For the actual parameters of interest, α, β, ρ, and γ_i, we used non-informative priors. Informative priors were used for the parameters of the dating uncertainty kernel for the age-dated fires. We used log-normal priors for k_0, k_1, and k_2, with means of 7.4, 2.7, and 0.6 years, and 95% confidence limits of 2.7–20.1, 1.0–7.4, and 0.37–1.0 years, respectively. A normal prior was used for d_s, with mean = 0 and standard deviation = 0.5. The posterior distributions for the regression parameters were calculated with an iterative method using an adaptive Markov chain Monte Carlo algorithm (Haario et al. 2005) implemented in C++.

RESULTS

Signs of fires were omnipresent in the studied landscape; all the 85 study plots had been burned at least once during the previous 220 years (Fig. 3). Scattered fire scars could be found in approximately half of the study plots, while post-fire regeneration cohorts and charred wood provided evidence for stand-replacing fires in the rest of the plots. None of the sample plots happened to fall in recently burned areas (though some were observed between plots), with the most recent fire sampled occurring in 1981. The average annually burned area over the whole
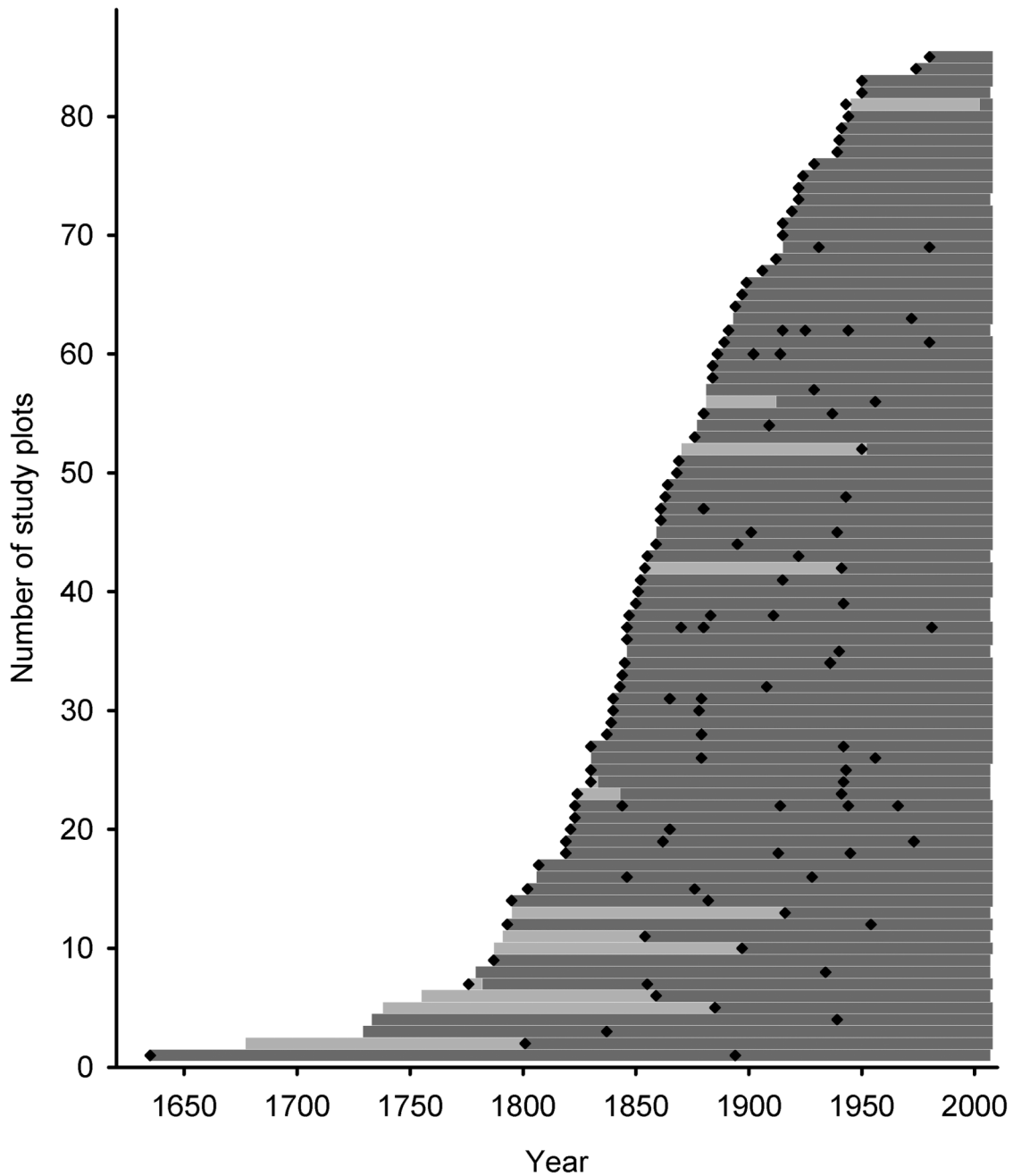
Fig. 3. Annual tree ring and fire chronologies of study plots arranged according to the earliest year of inferred fire occurrence. The age of oldest living trees is shown by dark gray bars, and fire years are indicated by black diamonds. Light gray bars denote dead wood samples with charred branch tips belonging to a previous tree generation.

study area during the last two centuries has been 1.3%, corresponding to a fire cycle of 77 years (Fig. 4).

The occurrence of forest fires has varied considerably during the last two centuries. The foremost change was the decreasing trend in the

annually burned area over the whole period. Average annually burned area decreased from 2.0% in the first half of the 19th century to 0.33% in the later half of the 20th century, corresponding to fire cycles of 50 and 300 years, respectively. Fires decreased especially after the mid-19th century. In the 1940s there was an intermediate peak in fires after which a rapid further decline in annually burned areas followed (Fig. 4).

In the southern part of the study area (in British Columbia and Alberta) our reconstruction is in good agreement with fire statistics of the area except for the 1940s where our reconstruction shows considerably higher burned areas (Fig. 5A). In the whole study area the 1960s and 1970s statistics and reconstructions show similar values but in the 1990s statistics report average annually burned areas that are higher than our upper confidence limit (Fig. 5B).

The full regression model was first fitted for the period 1900–2000, for which all the climatic factors were available. Of the climatic factors, GiR and MDC were positively, and the PDO index negatively, correlated with the burned area, indicated by corresponding regression parameters that were positive (or negative, respectively) with at least 95% posterior probability (Fig. 6). Since all climatic predictors were normalized to have a variance of 1, the magnitudes of the corresponding regression parameters show the relative importance of the predictors. The GiR index appears to be the single best climatic predictor of burned area. According to the posterior distributions, the regression parameters for JJA (γ_{JJA}) and road building date (ρ) were equally likely to be positive or negative, and hence did not show an effect on the burned area (Fig. 6A). Also, sample plot distance from roads (0.2–1.0 km) did not correlate with the burned proportions of the area (p = 0.7, Spearman's rank test).

Despite the correlation between the climatic factors and burned area, the climatic factors did not explain the decreasing trend in fires. The residual trend represented by β was clearly negative both for the period 1900–2000 and 1800–2000 (with posterior probability > 0.9999, Fig. 6A and 6B, respectively). Indeed, none of GiR, MDC, and PDO correlate significantly with year (p > 0.25 for each, Spearman's rank test). It is noteworthy that the summer temperature

index JJA does have a significant positive trend (p < 10^{-6}), but it does not have explanatory value in the regression model. This indicates that on a yearly level, JJA is not negatively correlated with fires, which would be necessary for it to explain the trend in fires.

Fig. 4 shows the average yearly burned proportion for the period 1800–2000, as predicted by the regression model. The prediction uses the maximum posterior density values for the parameters, estimated for the period 1800–2000 (Fig. 6B). Road building date and JJA were left out of the predictive model, based on the analysis for the period 1900–2000, and PDO and MDC were not used for the 19th century for which they were not available. The prediction falls well inside the 95% confidence envelope for the empirical reconstruction.

Regarding the dating error, represented by k_0, k_1, k_2, and d_s the analysis gave clear additional information only about the systematic scar dating error, d_s, that had its highest posterior density at −0.5 (Figs. 6A and 6B). This means that the fires dated based on fire scars are equally likely to have occurred during the previous as the currently given year.

DISCUSSION

Signs of past fires were ubiquitous in the large tract studied in northwest Canada despite the large proportion of wetlands (20%). In the 19th century average annually burned proportion of the landscape varied between 3% and 1% in different decades, corresponding to fire cycles of 30 to 100 years (Fig. 3); over the entire 19th century, the average fire cycle was approximately 60 years. These values fall well within the range of historical fire cycles reported in boreal North America, despite the mostly more southerly location of such studies (Zhang and Chen 2007). Most studies from boreal Fennoscandia to Central Siberia have also suggested past fire cycles of between 30 and 100 years, or somewhat longer (Niklasson and Granström 2000, Drobyshev et al. 2004, Wallenius et al. 2011). It seems that despite differences in dominant tree species, historical fire return intervals across large parts of the circumboreal forests have been less than 100 years, with the long-term and large-scale averages being around 50–80 years. However, it
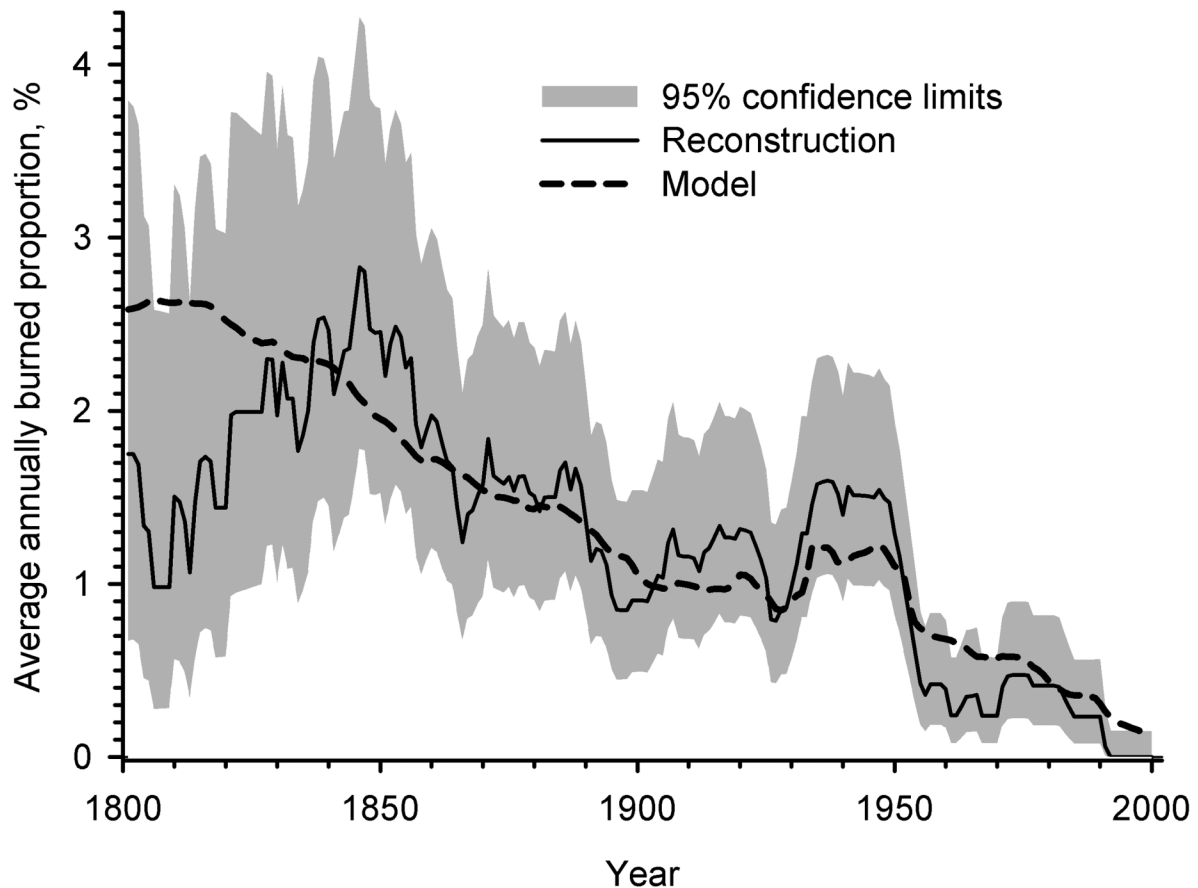
Fig. 4. Reconstructed and modeled burned proportions of the study area computed as a 20-year running average, with the 95% confidence envelope (gray) for the reconstruction. The model is the best 4-factor model including a trend, PDO, MDC of July and GiR as explanatory factors for the 1901–2000 period, but (due to lack of data) only the trend and GiR in the 19th century.

has to be noted that infrequently burned regions and forest types with fire cycles of hundreds of years are probably understudied (Wallenius 2002, Wallenius et al. 2010).

The decreasing trend in the annually burned areas detected from the 19th century to the modern day is similar to the general trend reported for more southerly regions of Canada, the western U.S.A. and Fennoscandia (Zackrisson 1977, Flannigan et al. 1998, Niklasson and Granström 2000, Heyerdahl et al. 2001, Zhang and Chen 2007). Two other field studies in northwestern Canada have also suggested a lengthening of fire cycles: fires started to decrease about 1860 in Wood Buffalo National Park (Larsen 1997) and in the late 20th century in Wood Bison Sanctuary and in Nahanni National

Park (Bothwell et al. 2004). The recent increase in annually burned areas seen in the fire statistics (Stocks et al. 2002, Kasischke and Turetsky 2006) appears to be relatively small in comparison with the previous decrease, i.e., the annually burned areas today are still at considerably lower levels than in the 19th century (Fig. 4).

The recent increase in fires has attracted public attention probably because it has been attributed to climate warming. The greater and widespread long-term decreasing trend is less well known and there is no consensus about the cause. Suggested causes for it have ranged, depending on the study and region, from fire suppression (Heinselman 1973) to climate change (Flannigan et al. 1998) and from more careful fire use by people (Kohh 1975) to excessive grazing by cattle
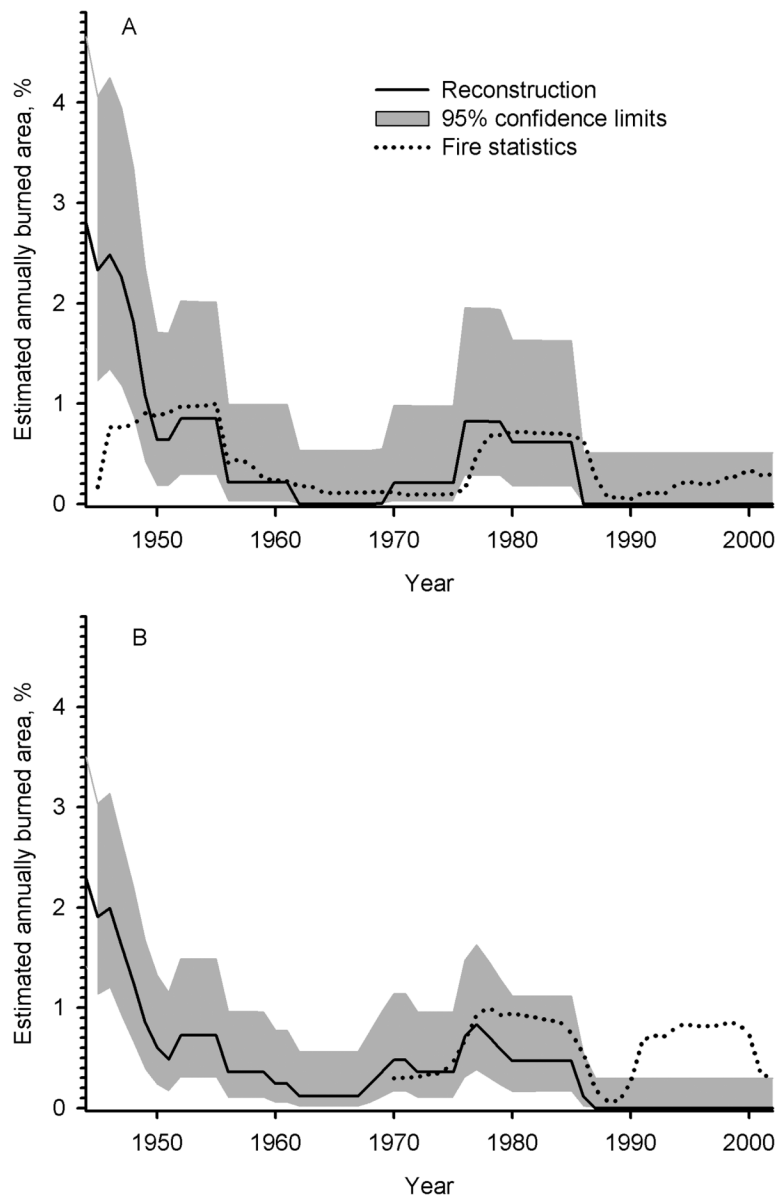
Fig. 5. Comparison of our reconstruction of annually burned proportion and the corresponding fire statistics reported for (A) the southern part of the study area in British Columbia and Alberta with long fire statistics and (B) for the whole study area. All data are presented as 10-year running averages. The fire statistics including all documented fires were acquired from Natural Resources Canada and fire management agencies of British Columbia, Alberta and Northwest Territories.

(Heyerdahl et al. 2001). The last-mentioned factor is clearly not relevant in northwestern Canada since there have never been large herds of domestic livestock in this part of the country but the other suggested causes deserve further attention.

Fire suppression in the study area started mostly after the 1950s, but the decline in fires started already in the mid-19th century and therefore fire suppression cannot explain the long-term declining trend in annually burned areas. The effectiveness of modern fire suppres-
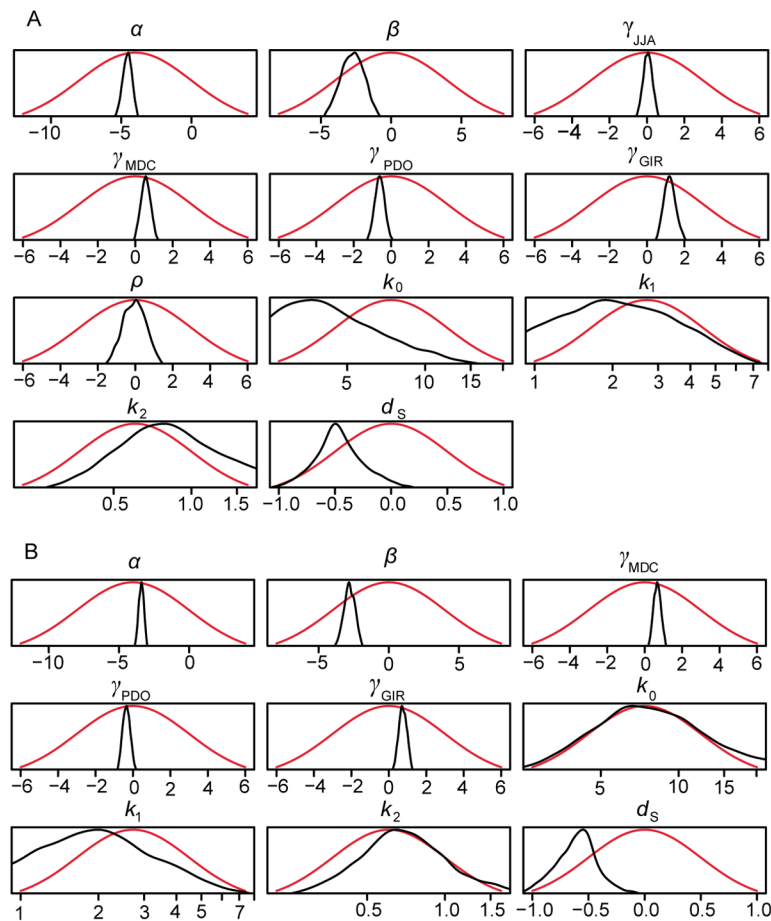
Fig. 6. Prior (red) and posterior (black) probability density functions for the regression parameters, vertically scaled to have the same maximum value, for visibility. (A) Estimates for the full model for the period 1900–2000. MDC, PDO and GiR each have predictive value for the burned area, as the posterior probability mass for each of those parameters is mostly on one side of the origin. In contrast, JJA and road building date (ρ) do not have a clear predictive value. (B) Estimates for the model that includes PDO, GiR, and fitted parameters only, estimated for the period 1800–2000.

sion has been questioned in North America (Bridge et al. 2005) but it probably has reduced the area burned during the latest few decades, especially in focused areas close to roads and human settlements (DeWilde and Chapin 2006). Indeed, more effective fire suppression close to roads could explain why our study plots (tied to the road network) did not burn in the 1990s as much as across the landscape as a whole (Fig. 4). Elevated oil, gas, and mineral exploration and development activity over the last two decades (Schneider 2002) has meant that these roads are well travelled by industry workers trained and equipped to put out fires. The lack of fires in

statistics from the 1940s is obviously due to poor detection and the under-reporting of fires (Stocks et al. 2002). The distance of study plots from roads (0.2–1.0 km) did not significantly correlate with the burned proportions of the landscape. This suggests that tying the study plot locations to a road network did not cause a marked bias in sampling the fire regime, at least within the range of distances tested. The same is suggested by the result that our estimates of average annually burned proportions were similar to aerially mapped fire statistics from the 1950s to the 1980s (Fig. 5).

We did not find evidence that road building

has affected annually burned proportions. This contrasts with the results by Arienti et al. (2009) from Alberta. They found that the density of forest fires is greater close to roads than deep in the forest. They suggested that this is because grassy roadside verges provide more flammable fuels for lightning-ignited fires than undisturbed forest vegetation. In the Russian boreal zone the forest fire density is also higher close to roads than further away (Kovacs et al. 2004). There the phenomenon is attributed to presence of humans as a source of ignitions. In our study area the missing evidence for the effect of roads might reflect a scarcity of data (there actually was a peak in the fire occurrence around the date of road building but it was not statistically significant) or because many roads were built on older paths and ancient trails and therefore the road building did not make a big difference with respect to human access.

Our results confirm that the reconstruction by Girardin and Sauchyn (2008), that MDC for July (Girardin et al. 2009) and PDO index (Duffy et al. 2005, Fauria and Johnson 2008) correlate with annually burned proportions in the northwestern Canada (Fig. 6). However, the effect of PDO varies in different studies. We found a negative correlation between the annual average PDO index and burned areas, similar to that reported by Duffy et al. (2005) from Alaska. In contrast, Fauria and Johnson (2008) suggest a positive correlation in Alaska and in the eastern side of Rocky Mountains (including our study area). As potential explanations for the discrepancy we suggest a possible lack of geographic detail, or the low-pass and high-pass filtering of the PDO index, in the study by Fauria and Johnson (2008).

Despite the observed correlations between GiR, MDC for July and PDO index and the annually burned proportion of the landscape, there was a clear residual decreasing trend in fires which was not explained by the climatic indicators. The climatic indices did not themselves show any trend. The summer (June–August) temperature was the only climatic index with a trend, but did not have predictive value in the regression model. In conclusion, the decreasing trend in fires has to be explained by some other factors, which were not included in our analysis. If the unknown explanatory factor is climatic, it has to be some signal, which has a strong temporal trend, and which is sufficiently independent of the factors included in our analysis.

As an alternative to climatic explanation to changes in fire regimes, Larsen (1997) hypothesized that the fur trade period could have brought a reduction in human caused fires in the region. Samuel Hearne, an officer of the Hudson Bay Company, visited the study area in 1772, and during the following decades fur trading posts were established here and there throughout the area. By the mid-19th century fur trapping had become an important part of the life and economy of the native people. This change from moose hunting to fur trapping may have resulted in a decrease in human-caused forest fires because moose prefer young forests whereas the most lucrative fur-bearing animals do not, and hunter-trappers probably try to promote habitat for their most valuable prey. We do not have data about the fur trade and its effect on the forest fires. However, there are several studies demonstrating that fire was a versatile tool for the native Americans (Lutz 1959, Lewis 1977, Barret and Arno 1982, Russell 1983). Also European settlers caused forest fires in North America, land clearing being the most important documented cause of forest fires in the late 19th century (Sargent 1884).

According to the unanimous view of 19th century foresters (Sargent 1884, Blomqvist 1888, Bell 1889), fires were mostly human caused in the past, whereas at present, fires in the northern Canada are mostly lightning ignited (Stocks et al. 2002). The earliest fire statistics from Canada report that people were responsible of more than 95% of the forest fires during the 1914–1917 period (Lewis 1920). According to the National Forestry Database (2010) the percentage of human caused fires during 1990–2008 is about 54% for the same provinces. The possibility that a decrease in human caused ignitions significantly contributed to the decrease in fires in our study area, and perhaps in other parts of North America, at least merits serious consideration and additional research.

ACKNOWLEDGMENTS

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