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Three centuries of annual area burned variability in northwestern North America inferred from tree rings

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Abstract: Annual area burned (AAB) variability in northwestern North America was inferred from 38 tree-ring width chronologies widely distributed across boreal regions and spanning the past 300 years and the minimum 1833–1998 interval. AAB estimates accounted for up to 61% of the variance in AAB observed from 1959 to 1998, and were verified using a split sample calibration-verification scheme. Spatial correlation maps of gridded temperature and precipitation data provided an indication of the reliability of the reconstruction to approximate fire-conducive climate variability beyond the period of calibration. Singular spectrum analysis and analysis of variance suggested that AAB has significantly changed during the course of the past 150 years toward increasing variance. Recent 1959–1998 decadal changes in AAB of northwestern North America fitted well within an oscillatory mode centred on 26.7 years and accounting for 21.1% of the variance in the reconstruction. As in previous studies, the current findings suggest that AAB is correlated to seasonal land/ocean temperature variability and that future warming could lead to greater AAB. However, the study has the weakness of not accounting for complex interactions between climate and ecosystem processes and thus its results should be interpreted with caution. We suggest that a calibration model conducted on multiple types of fire proxies (tree rings, charcoal data, fire scars and stand-establishment records) could be relevant for addressing these weaknesses.

Key words: Forest fires, area burned, fire history, dendrochronology, dendroclimatological reconstruction, Alaska, Canada, late Holocene.

Introduction

Wildfire is a primary natural process that controls the physical and biological attributes of boreal forests, shapes landscape diversity and influences biogeochemical cycles (Weber and Flannigan, 1997). The mosaics of different vegetation types are to a large extent an expression of their respective fire regimes and many boreal tree species have adapted to fire. Wildfire responds rapidly to changes in weather and climate in comparison with vegetation – the rate and magnitude of fire regime-induced changes to the boreal forest landscape can greatly exceed anything expected as a result of climate change alone (Weber and Flannigan, 1997). In addition, watershed-scale wildfires have profound effects on water quality in boreal surface waters. Trees take up considerable amounts of water through the process of transpiration and their removal can lead to enhanced erosion, leaching, and particle and nutrient transport from soils to streams after heavy rainfalls (Prepas *et al.*, 2003). Changes in nutrient fluxes after wildfires can lead to a complex series of biological changes that can affect the structure and function of aquatic ecosystems. Lastly, at very large scales, wildfires have profound effects on fire emissions into the atmosphere, including emissions of carbon dioxide (CO_2), carbon monoxide, methane, long-chain hydrocarbons and carbon particulate matter.

In the past four decades or so, significant progress has been made in characterizing fire regimes and fire-conducive climate variability in Canada and Alaska. These advances include the development of a daily forest fire danger rating system (eg, Van Wagner, 1987), the gathering of fire statistics (Kasischke *et al.*, 2002; Stocks *et al.*, 2003), and a number of studies relating numerous fires over many years to climate variability (eg, Flannigan and Harrington, 1988; Skinner *et al.*, 1999; Beverly and Martell, 2005; Duffy *et al.*, 2005; Flannigan *et al.*, 2005; Macias Fauria and Johnson, 2006). These fire studies have spatial domains ranging

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from hundreds of square kilometres to continental scale, and a temporal range of 10 years to about 80 years. The temporal scale in fire studies is often limited by the availability of fire statistics and meteorological data. In this matter, significant efforts have been devoted to the long-term reconstruction of past fire activity from fire scars, stand-establishment records (eg, Larsen, 1997; Bergeron *et al.*, 2004), charcoal abundance in lake sediments (eg, Larsen and MacDonald, 1998; Carcaillet *et al.*, 2001; Lynch *et al.*, 2002) and ammonium concentration $[NH_4^+]$ in ice cores (Yalcin *et al.*, 2006). These efforts aim to increase our understanding of the linkages between multicentury-long fluctuations in climate, vegetation and fire activity at local and regional scales.

Recent achievements also include long-term statistical estimation of past fire activity variability from tree rings and tree-ring derived proxy records (eg, Westerling and Swetnam, 2003; Girardin *et al.*, 2006a; Girardin, 2007). Trees in temperate regions produce annual radial increments, where changes in ring width from one year to the next reflect changes in precipitation and temperature, as well as other factors (Fritts, 2001). Trees can also sense climate variations that promote fire activity, such as fluctuations in the strength of atmospheric longwave patterns (ie, location and magnitude of high- and low-pressure systems) and seasonal droughts (Larsen, 1996; Girardin *et al.*, 2006b). Despite the increasing importance of human activity as a source of fire ignition, dry forest fuels and wind remain major contributors to large stand-destroying fires (Johnson, 1992). Spatial and temporal patterns of annual tree radial increments, as measured across extensive networks, can be used to infer area burned variability and, additionally, to extend area burned records for periods during which there were no records of fire activity.

In this paper we use a newly available network of site tree-ring width chronologies from primarily across boreal Canada to statistically reconstruct multicentury annual area burned (AAB) variability for northwestern North America. In this region, the frequency of large fire years and, consequently, AAB have been steadily increasing since 1970 (Kasischke and Turetsky, 2006). Deeper seasonal thawing as a consequence of global warming is anticipated to further accelerate these trends. Through the tree-ring archives we provide a long-term historical context for recent decadal variations in AAB (1959–1999) and show that these have historically been well correlated to seasonal land temperature and precipitation variability. Furthermore, we demonstrate the relevance of AAB reconstruction for analysis of oceanic and fire weather linkages. It is now becoming clearer that the global ocean exerts a significant influence on fire weather in Canada through its effect on large-scale atmospheric circulation (Skinner *et al.,* 2006). Unveiled relationships between fire signature years and ocean conditions are promising for long-range forecasting of fire weather (Skinner *et al.,* 2006). Weather prediction limits based on the intrinsic variability in the atmosphere are thought to be of the order of two weeks. However, ocean variability occurs at a much slower timescale, which implies that seasonal fire danger prediction could be possible (Skinner *et al.,* 2006). In this regard, the contribution of tree-ring based reconstructions of AAB can be significant as they can increase our confidence in these statistical relationships.

Data and methods

Description of the annual area burned data

Data for large forest fires (size > 200 ha) from the Canadian Large Fire Data Base (LFDB; Stocks *et al.,* 2003) and from the Alaska Historical Fire Data Base (Bureau of Land Management, Alaska Fire Service; retrieved 12 November 2007 from http://agdc.usgs.gov/data/blm/fire/index.html) were used in this study to calibrate an annual area burned (AAB) model. These fires represent only a very small percentage of the fires but account for most of the area burned (Kasischke *et al.*, 2002; Stocks *et al.*, 2003). Fires that occurred in the Southern Arctic, Taiga Plains, Taiga Shield (west of 90°W), Taiga Cordillera and Pacific Maritime ecozones (Figure 1) were compiled along with the Alaska fire data, producing a time series of AAB (in hectares) covering the period 1959–1999. As fire is highly variable between years, the use of a large number of samples provides some statistical smoothing. Shapiro-Wilk normality tests indicated right-skewness in AAB frequency distributions (p = 0.000, where p-values below 0.05 are considered small enough to declare the fit with the normal curve poor). The logarithmic transformation (LOG) was found to provide an adequate data transformation to meet the normality requirement (after logarithmic transformation: $p > 0.200$). Next, a positive trend in AAB data was removed using a linear least square fitting. The period of calibration (1959–1999) was considered too short for a robust reconstruction of the trend (to be considered robust, a calibration model's residuals should not contain a linear trend or autocorrelation, and calibration model predictive skills should be greater than would be expected by chance; see Wilson *et al.*, 2006). Furthermore, detrending of the area burned data was justified by the changing quality of forest-fire statistics over both time and space (Kasischke *et al.*, 2002). The size of the protected area effectively under fire management increases over time. Forest-fire management agencies have traditionally focused their efforts in areas where they judged fire might have its most significant impact on public safety, property and forest resources. It is widely accepted that not all the fires that occurred in lower priority areas were detected, reported and included in annual fire statistics. The effects of land use history on forest structure, fuel accumulation and fire behaviour and influences through human settlement could also be confounding factors (Weir *et al.,* 2000; Westerling *et al.,* 2006). We hence preferred to focus on the reconstruction of year-to-year and decade-to-decade variability.

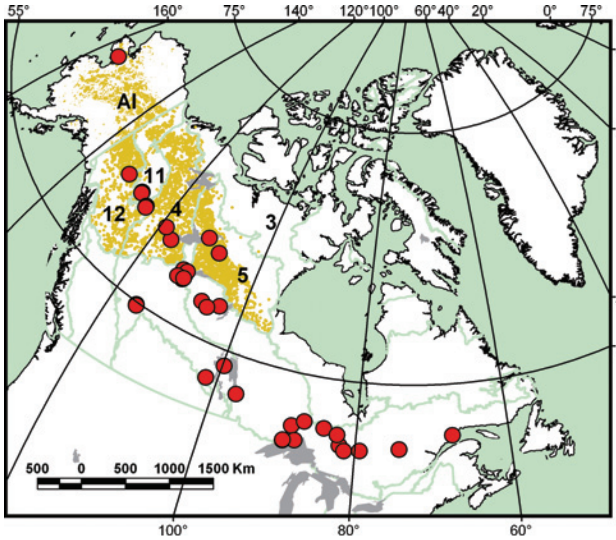

Figure 1 Distribution of the 38 tree-ring width chronologies used as annual area burned (AAB) predictors and domain under study (distribution of fires is shown). Numbers and boundaries refer to ecozones: 3, Southern Arctic; 4, Taiga Plains; 5, Taiga Shield; 11, Taiga Cordillera; 12, Pacific Maritime and Al, Alaska, The percentage (%) of AAB accounted for by each ecozone relative to the total AAB is respectively 0.2%, 36.3%, 25.2%, 2.3%, 11.1% and 25%

Description of area burned predictors

A set of site tree-ring width chronologies that demonstrated a satisfactory correlation with the log-transformed AAB record was identified and subsequently used for statistical reconstruction. Site tree-ring width chronologies are defined as averages of annual ring width measurements for one to several cores per tree and from a sample of trees (typically ~20) growing on similar ecological sites. Spearman correlation analysis was used to screen the AAB record against 105 candidate tree-ring width chronologies distributed across Canada, Alaska and northern USA, and covering the minimum 1833–1999 interval (Contributors to the International Tree-Ring Data Bank, 2004; Girardin *et al.*, 2006b). About half of the data were distributed within the domain under study: 28 sites in Alaska and 29 in northwestern Canadian ecozones. Tree-ring width chronologies located outside the domain were also included in this screening as atmospheric longwave patterns associated with extreme fire years can cover vast land areas (Skinner *et al.*, 1999; Macias Fauria and Johnson, 2006). The 1833–1999 period was chosen to maximize the length of the period of analysis, the distribution of chronologies across Canada and sub-signal strength (used to define a portion of a given chronology with a strong common signal). It is difficult to know *a priori* which site tree-ring width chronologies are potentially useful records of climate associated with area burned variability. Therefore, some sort of variable screening is desirable to eliminate useless data (Cook *et al.*, 2002). Note that, prior to screening, all tree-ring width measurements were processed to remove unwanted age/size-related trends using cubic smoothing splines of 66% of the ring width series length with 50% frequency response (Cook and Kairiukstis, 1990). Serial persistence was removed from these 'standardized' measurement series using autoregressive modelling, and bi-weight robust means of the 'residual' measurement series were computed to create the site tree-ring width index chronologies. All index chronologies were constructed using the ARSTAN program (Cook and Holmes, 1986).

The correlation screening revealed a subset of 38 chronologies (Figure 1; see Appendix 1) out of the original 105 that correlated at $p < 0.10$ (Spearman $r > |0.264|$) with the AAB record (or its backward and forward lags) over the common period 1959–1999. Sensitivity analysis in which the p-level of the correlation screening was modified to $p < 0.15$ confirmed the robustness of the final reconstruction (calibrated on a subset of 50 chronologies from which seven originated from Alaska). Sensitivity tests conducted after exclusion of chronologies located outside the domain of study further confirmed the robustness of the final reconstruction (calibrated on a subset of 43 chronologies).

Statistical reconstruction of the area burned

Utilizing only the common period would result in a reconstruction covering only the period 1833 to present. To extend the reconstruction further back in time, a varying time series technique was employed (eg, Cook *et al.*, 2002; Wilson *et al.*, 2006). Eight submodels were developed for the reconstruction, starting with a maximum of 38 chronologies and removing chronologies in subsequent submodels. In each reconstruction submodel, the available chronologies were transformed into non-rotated principal components (PCs) to remove multicollinearity (Cook and Kairiukstis, 1990). Fire-conducive weather across Canada exhibits strong regional similarities that are largely due to the common influence of large-scale features of oceanic and atmospheric circulation (Skinner *et al.*, 1999, 2006; Girardin *et al.*, 2006b). Therefore, it is appropriate to summarize the dominant information contained within the tree-ring data set into a new set of uncorrelated variables (the approach is very similar to that employed in the reconstruction of large-scale sea surface temperature and sea-level pressure fields; eg, Cook *et al.*, 2002). The use of PCs also has the advantage of filtering noise from the data set (eg, effects of stand disturbances from fires or insect herbivory). The PCs were derived from a correlation matrix (program SYSTAT, 2004) so that all chronologies contributed equally to the clustering of samples, independently of the variance exhibited by each one. Two PCs with their backward and forward lags were retained for subsequent analyses.

For each submodel, a stepwise multiple regression (SYSTAT, 2004) employing a backward selection was used to fit a linear model relating the log-transformed AAB record (period 1959–1998) to the PCs:

$$Y_{\log j} = \alpha + \beta_1 x_{1j} + \beta_2 x_{2j} + \beta_m x_{mj} + \varepsilon_j \qquad (1)$$

where $Y_{\log_j}$ was the log-transformed AAB, x_j the PCs (total of six candidate predictors), β the regression coefficients, and ε_j the error. Once the regression coefficients were estimated for the calibration period, they were applied to the PCs for as far back as possible to produce a series of log-transformed AAB estimates.

The robustness of each calibration was tested using a split sample calibration-verification scheme. For each submodel, two subcalibrations of the periods 1959–1978 and 1979–1998 were conducted using the selected PCs in Equation (1), and the estimated regression coefficients were applied to the PCs over the verification periods 1979–1998 and 1959–1978. The strength of the relationship between the reconstruction and observations over the verification periods was then measured by the reduction of error (RE) and the product means test (PM) (see Appendix 1; Cook and Kairiukstis, 1990).

The final AAB reconstruction (in log hectares) was built after piecing together the segments of the eight submodels. To avoid artificial variability changes in AAB inherent to a decreasing number of predictor chronologies with time, we scaled the mean and variance of the less replicated submodels (and the associated standard error) to that of the most replicated one (ie, 1833–1998) (Wilson *et al.,* 2006).

Sensitivity analyses of biases

As in previous statistical reconstructions of fire activity (Girardin *et al.*, 2006a; Girardin, 2007), AAB estimates could be biased in that regions with greater fire incidence will be weighted accordingly in the reconstruction. As a means of validating the spatial coverage, AAB estimates and observations were correlated with seasonal averages of May–August Climate Research Unit (CRU) TS 2.1 global land temperatures and precipitation (Mitchell and Jones, 2005). The CRU TS 2.1 data are interpolated to a 0.5° latitude by 0.5° longitude grid and cover the time frame 1901 to 2002. The obtained correlation values at each grid point were used to create land temperature and precipitation spatial correlation maps. Correlations were computed over two periods, 1901–1958 and 1959–1998, in order to test the stationarity of the AAB estimates/climate relationship and to provide some means of validation of AAB estimates over a period independent of the full calibration. The May–August period was chosen for correlation as it covers the fire season in Canada (Stocks *et al.*, 2003) and was previously shown to correlate well with fire cycles in Alaska (Kasischke *et al.*, 2002).

Results and discussion

Multicentury annual area burned variability

Figure 2 presents the full reconstruction and associated calibration and verification statistics. In the replicated submodels (no. of chronologies >20) AAB estimates account for up to 61% of the variance in observations. The smallest percentage of common

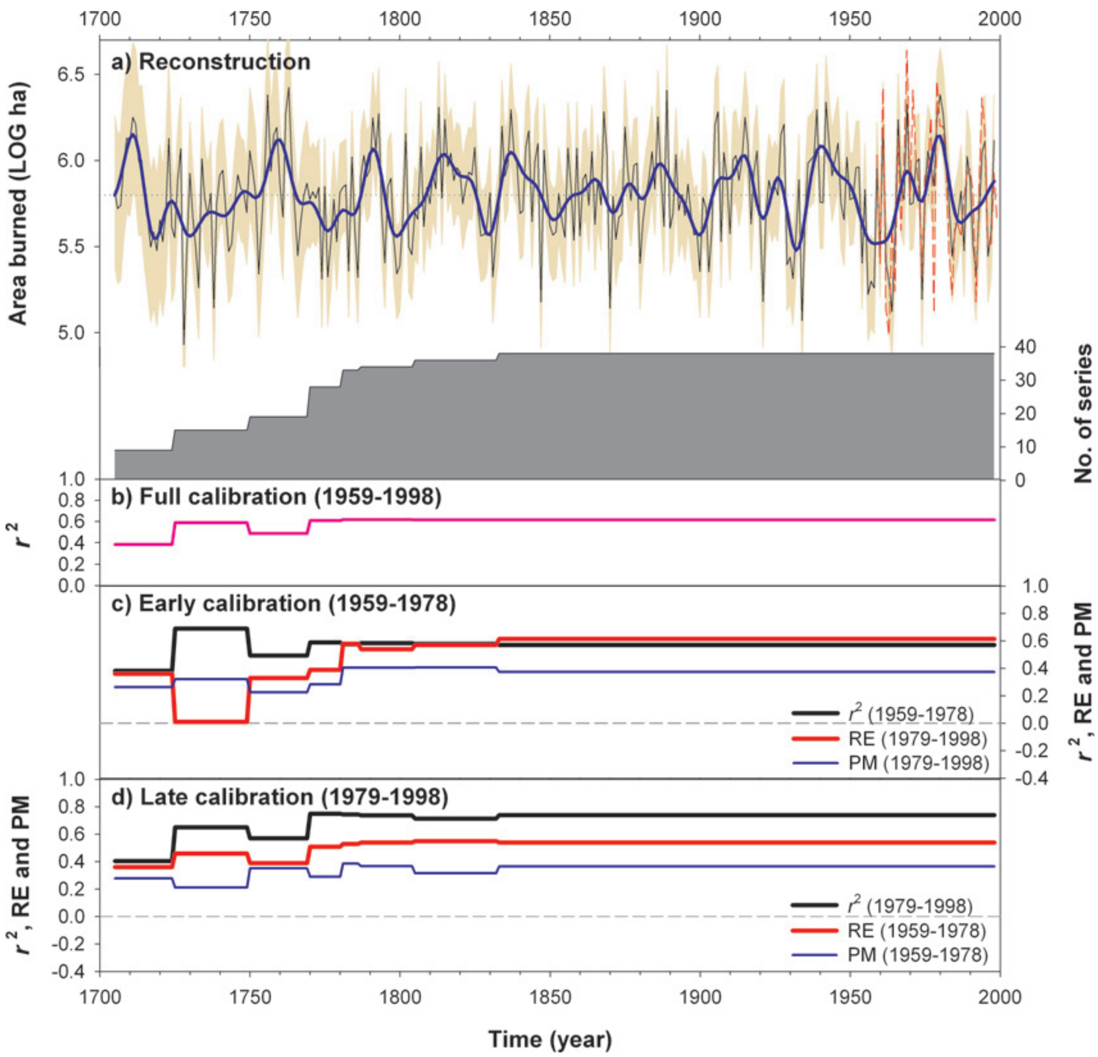

Figure 2 Statistical reconstruction of the logarithmic-transformed annual area burned (AAB) in northwestern North America. (a) Observed and reconstructed AAB with standard error; a 10-yr polynomial fitting across the data is shown. The shaded histogram denotes the number of site tree-ring width chronologies utilized through time. (b) Full period (1959–1998) calibration r^2 statistics. (c) Early period (1959–1978) calibration r^2 and late period (1979–1998) verification RE and PM statistics. (d) as in (c) but periods are reversed. The r^2 is square of the multiple correlation coefficient, RE is reduction of error and PM is product means test (divided by 10). The RE is a measure of shared variance between the observed and modelled series and is usually lower than the r^2; a positive value (RE > 0) signifies that the regression model has some skill. A significant PM result (PM > 1.73) indicates that the magnitude and the direction of year-to-year changes are statistically significant

variance is 38%. Verification statistics are markedly high after 1750. Prior to 1750, the quality of the reconstruction may arguably be questionable as spatial coverage decreases. We nonetheless have some confidence in AAB estimates covering 1705 to 1750 as the PM statistic remains high and the RE, although low, remains above the satisfactory level. Analyses of model residuals with the Durbin-Watson statistic shows no significant autocorrelation at the 1% probability level in any of the submodels. Overall, the mean correlation between the eight submodels over their common period 1833–1998 is high ($r = 0.90$ with 99% confidence interval [0.87, 94]), suggesting that they are all reproducing a common environmental signal.

AAB reconstruction shows striking decade-to-decade variability throughout much of its time coverage with the most pronounced variations from 1750 to 1850 and during the past 50 years (Figure 2). Regime shift detection analysis (Rodionov, 2006) indicated significant increases in the mean AAB in 1755, 1787, 1813, 1834 and 1966 (see Figure 4a). The duration of high AAB episodes was from 7 to 17 years, the longest episode being 1966–1982. The period of lowest AAB was 1956 to 1965. Singular spectrum analysis (SSA), a robust data-adaptive method of extracting signals from noise in time-series (Elsner and Tsonis, 1996), identified a pronounced 26.7 years oscillatory behaviour in the reconstruction (Figure 3a), explaining 21.1% of the variance (program AutoSignal version 1.5, AISN Software, 1999). The oscillatory variability had its greatest amplitude during the mid- to late-twentieth century and related well to the decadal fluctuations identified by the regime shift method. The exclusion of the periodic component from AAB reconstruction and the application of the regime shift analysis to the resultant time series yielded no significant change in mean (Figure 3b).

In common with the SSA results, analysis of variance over a sliding window of 25 years also showed increased AAB variability in recent years (Figure 3c). An *F*-test revealed that the variance in the 1920–1998 period was significantly greater than during the preceding period 1705–1919 (p(F-test) = 0.031; if restricted to 1833–1919, p(F-test) = 0.042). Changes in variance throughout the twentieth century remain noticeable even after the removal of the 26.7 years periodic component (Figure 4d; p(F-test) = 0.022). Overall, the combined results from the SSA and analyses of variance suggest that AAB variability over northwestern North

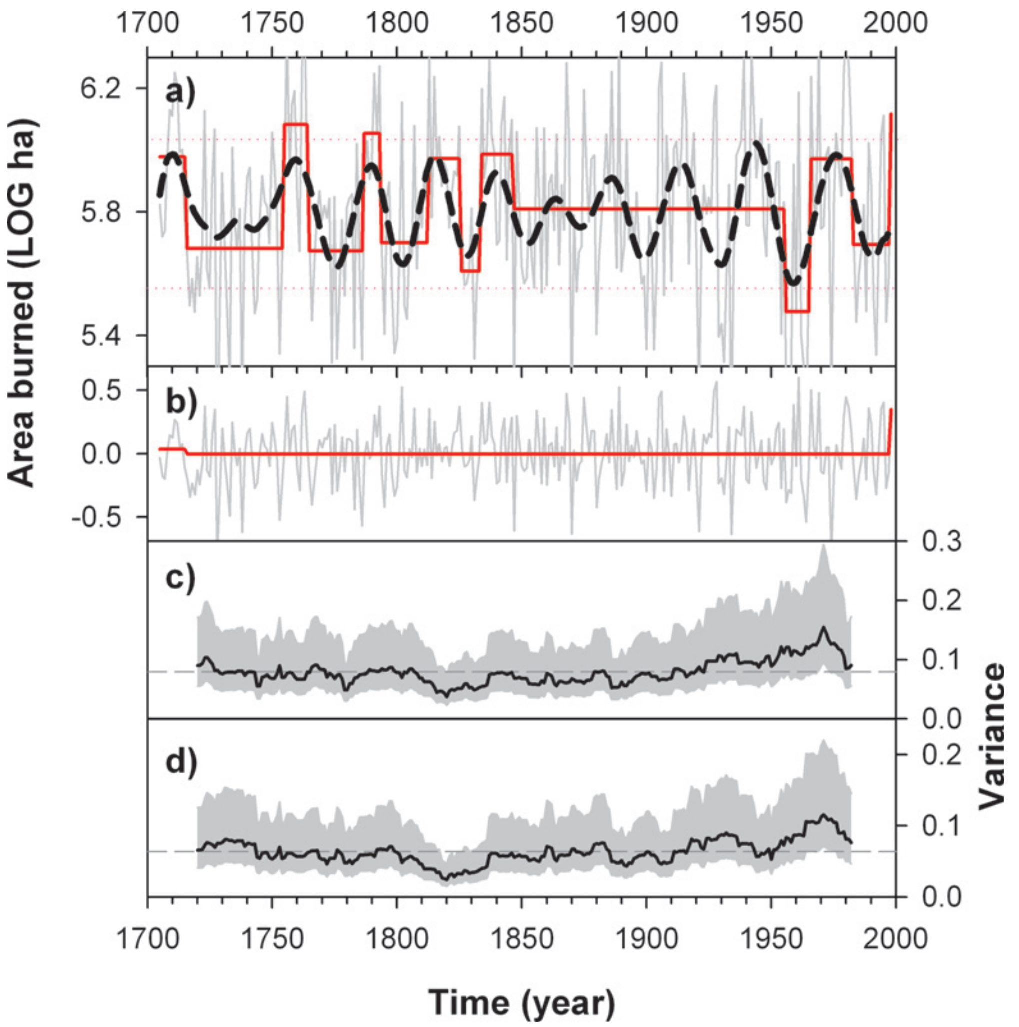

Figure 3 Time series analyses. (a) Retained 26.7 yr/cycle signal component (thick dashed line) and regime shift detection (thick solid line) with correction for serial correlation (AR(1)). Regime shift detection allows verification that changes in the mean from one period to another are not just a manifestation of a red noise process (probability $\sigma = 0.10$, cutoff length = 10 years; outliers weight parameter = 6; parameter AR(1) = 0.13 following the IPN4 method of Rodionov, 2006). (b) Regime shift analysis after removal of the periodic component from the annual area burned (AAB) reconstruction. (c) 25-yr overlapping sliding window of variance (thick line) with 95% confidence levels (shaded area) of AAB estimates (window central value is shown). (d) Variance analysis after removal of the periodic component

America has significantly changed during the course of the past 150 years and seemingly at multiple timescales.

Regions with greater fire incidence and tree-ring data replication are likely to be weighted accordingly in the AAB reconstruction. Correlation analysis between the most replicated submodel and observed AAB records taken individually for each ecozone shows a high correlation for the Taiga Plains and Pacific Maritime ecozones (both at p(two-sided) < 0.001; period 1959–1998), a low correlation for the Taiga Shield West ecozone ($p = 0.039$), and no correlation for the Taiga Cordillera ($p = 0.506$). For Alaska, the correlation is not significant over the entire interval 1959–1998 ($p = 0.145$), but is significant over the 1959–1987 period ($p = 0.004$). Hence, these estimates seem to adequately approximate fire activity where most of the area burned occurred (Figure 1)..

Spatial correlation maps for the 1959–1998 interval (Figure 4) indicate similar patterns between AAB estimates, AAB observations, temperature, and precipitation over Canada. Specifically, AAB, for both estimates and observations, is positively (negatively) correlated with temperature (precipitation) over Canadian ecozones. The spatial pattern for precipitation is more variable than for temperature, a likely manifestation of the presence of the mountain ranges (Macias Fauria and Johnson, 2006). When applied to the period 1901–1958, the spatial correlation fields resemble that of the 1959–1998 interval, albeit more weakly in western Canadian regions. AAB estimates also appear to capture some of the variability in the eastern interior of Alaska. Although this region is known for its high fire activity (Kasischke *et al.,* 2002), AAB estimates are not well correlated with the entire region affected by fire (Kasischke *et al.,* 2002; Figure 1). The correlation pattern over Alaska beyond the period of calibration is also poor, although some improvements are noticeable if analyses are conducted on low-pass filtered AAB estimates (Figure 5). This lack of spatial coherence between Alaska and Canadian ecozones could be inherent to the dynamics of large fires and climate influences on each side of the mountain ranges (see Macias Fauria and Johnson, 2006). Until it can be shown otherwise, the current results should be interpreted with caution and not directly applied to the entire domain under study. Follow-up studies should consider downscaling and centering a reconstruction on Alaska.

Linkages to the global ocean

The tropical Pacific ocean–atmosphere system (equatorward of ~30°) has a significant influence on global climate at timescales ranging from interannual to multidecadal (Schneider *et al.,* 2002;

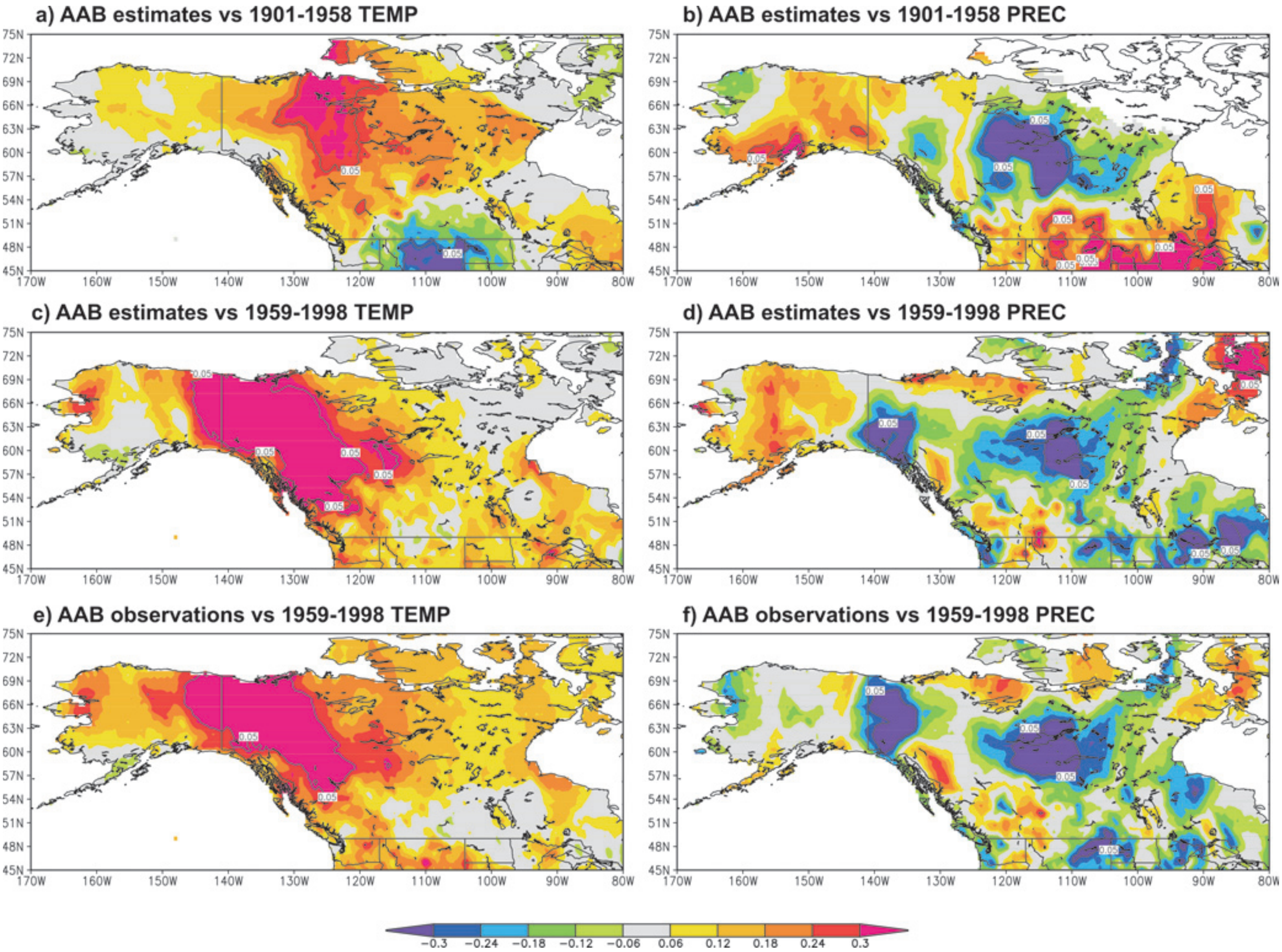

Figure 4 Correlation between annual area burned (AAB) estimates and seasonal averages of May–August temperatures and precipitation over periods 1901–1958 (a, b) and 1959–1998 (c, d). (e, f) Same as (c, d) but for AAB observations over 1959–1998. The contour line delineates the 5% significance level. All data were ranked and detrended prior to analysis

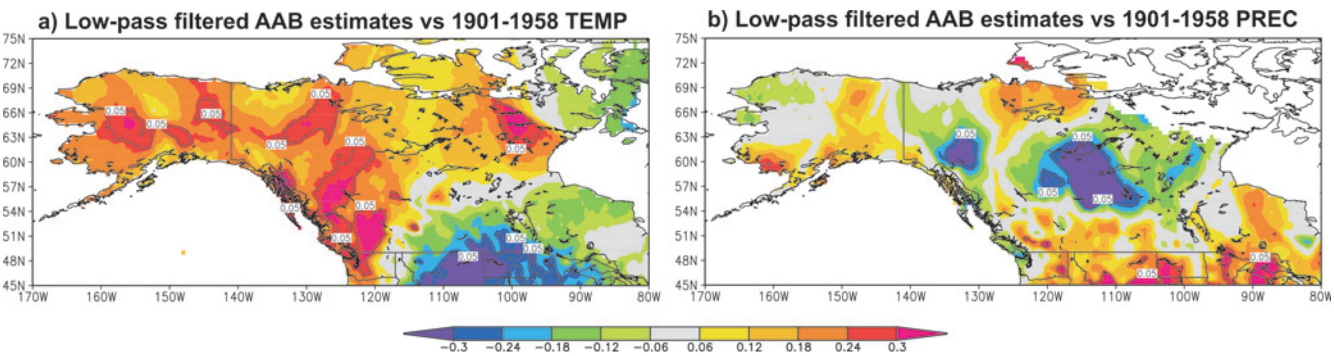

Figure 5 Correlation between low-pass filtered annual area burned (AAB) estimates (5-yr polynomial fitting) and seasonal averages of May–August temperatures and precipitation over 1901–1958. The contour line delineates the 5% significance level. All data were ranked and detrended prior to analysis

Wu and Liu, 2003; Girardin *et al.,* 2006b; Skinner *et al.,* 2006; Wilson *et al.,* 2007). The presence of a bidecadal oscillation (in the order of ~20 to 30 years) in the North Pacific sector has often been reported (Schneider *et al.*, 2002; Wu and Liu, 2003; Wilson *et al.*, 2007). In this regard, the observation of a similar decadal frequency in AAB is intriguing. The debate as to whether this behaviour in the Pacific originates from the tropical region or whether it is caused by atmosphere–ocean instability remains unresolved (An *et al.,* 2007). Several hypotheses have indeed been put forward as to the origin of the presence of decadal variability. By means of fast atmospheric transport and/or slow overturning circulation in the upper ocean, extratropical–tropical linkages are frequently assumed to act as conveyors for transport of extratropical climatic anomalies (poleward of ~30°) to the tropics (Wu *et al.*, 2006). Conversely, the tropics are also said to exert a significant influence on extratropical climate (Deser *et al.,* 2004). Atmospheric responses to sea surface temperature (SST) anomalies in the tropical Pacific would determine ocean surface temperature conditions over much of the global ocean, and ultimately affect the large-scale atmospheric circulation over North America (Schneider *et al.,* 2002; Wu and Liu, 2003; Skinner *et al.,* 2006).

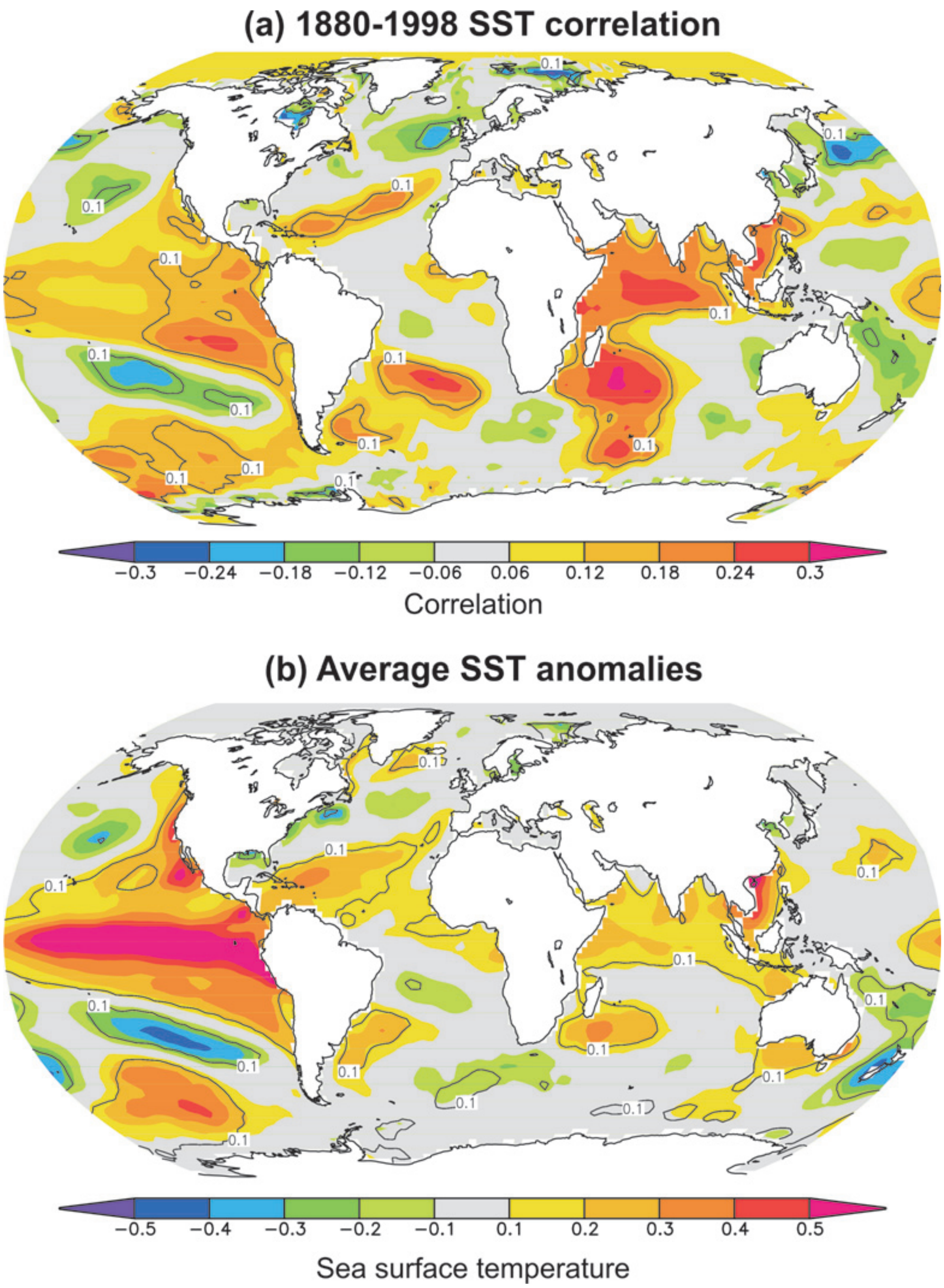

Figure 6 (a) Correlation between annual area burned (AAB) estimates and December–February seasonal averages of global ocean sea surface temperature (SST) anomalies, period 1880–1998. (b) Average SST anomalies (°C) at times of the 19 highest AAB estimates during this same period (1885, 1888, 1904, 1905, 1914, 1926, 1927, 1938, 1941, 1942, 1945, 1960, 1965, 1968, 1978, 1979, 1980, 1994 and 1997). The contour line delineates the 10% *p*-level. The SST anomalies were calculated using the ERSST NCDC v2 data set of Smith and Reynolds (2004) on a 2-degree grid; data were detrended prior to analyses. The December–February season was chosen in accordance with Skinner *et al.* (2006)

We verified whether temporal variability of our AAB estimates could be related with the more slowly varying ocean. AAB estimates were correlated with seasonal averages of a December–March extended reconstruction of SST (Smith and Reynolds, 2004). The SST data are interpolated to a 2° latitude by 2° longitude grid and cover the time frame 1880 to 2002. An anomaly composite map on the 85th percentile of AAB over that same period was also created to assess whether extreme fire years could be subject to non-linear forcing mechanisms. As indicated in Figure 6a, the relatively high temporal variability of AAB can be shown to be related with the more slowly varying SST, particularly that of the tropical and South Pacific and Atlantic as well as Indian Oceans (all at $p < 0.01$). Additionally, warm SST in the tropical Pacific basin appears strongly coincident with extreme fire years ($p = 0.005$). These results lend credibility to previous findings from Skinner *et al.* (2006), who found that from 1953 to 1999, the effect of variability in the global ocean, and particularly that of the tropical regions, was clearly detectable in the boreal and taiga regions of northwestern Canada. Several recent studies have documented the importance of decadal variations in North Pacific and North Atlantic SSTs on fire occurrence and extent in the Rocky Mountains and elsewhere (eg, Schoennagel *et al.*, 2005; Kitzberger *et al.*, 2007; Le Goff *et al.*, 2007). Although the interactions among the various sources of variability (eg, solar, volcanic, tropical and extratropical forcing) are still not entirely understood, these results should encourage follow-up efforts to elucidate the patterns of covariance between AAB and the global ocean and for the development of long-range fire severity predictions (Skinner *et al.,* 2006).

Limitations and challenges

We recognize that there are weaknesses to this study: complex interactions between fire, weather and climate, physiographic features, land use and vegetation are not accounted for by our analysis. The suitability of this reconstruction for inferring secular changes (ie, lasting from century to century) in the AAB is also questionable because of the detrending and prewhitening procedures applied to the tree-ring width measurement series (Cook *et al.*, 1995). The contribution of other types of fire archives, such as high-resolution fire charcoals found in lake and bog sediments (eg, Larsen and MacDonald, 1998; Carcaillet *et al.*, 2001; Marlon *et al.*, 2006), fire scars and historical fire frequency inferred from stands-establishment records (eg, Larsen, 1997; Bergeron *et al.*, 2004), could be valuable in attempts to reconstruct past fire conditions through the calibration of multiple sources of fire proxy data. In support of these efforts, it is interesting to see that the last four peaks in AAB (1890, 1915, 1940 and 1980; Figure 2) are almost identical to four peaks identified by Larsen (1996) in northern Alberta, Canada, using lifetable analysis of stands-establishment records (1880–1890, 1915–1920, 1940–1950 and 1980). High fire activity recorded by an ice core in Yukon during the 1760s, 1780, 1840s, 1860s, 1880–1890s, 1920–1940s and 1980s (Yalcin *et al.*, 2006) also match peaks in the statistical reconstruction of AAB. There is hence a pattern of similarity among the different records that is worth further attention.

The projected impacts of human-induced climate changes in the boreal forest are usually associated with increased fire activity (Gillett *et al.*, 2004; Flannigan *et al.*, 2005; Bergeron *et al.*, 2006). Although dry forest fuels and wind remain major contributors to large stand-destroying fires (Johnson, 1992), there is increasing evidence of linkages between yearly and decadal temperature variability and changes in the area burned (Gillett *et al.*, 2004; Flannigan *et al.*, 2005; Girardin, 2007). As in previous studies, the current findings suggest that AAB is correlated to seasonal land/ocean temperature variability. This implies that future warming (Intergovernmental Panel on Climate Change (IPCC), 2007) could lead to greater area burned in northwestern North America. Although precipitation at high latitude is also expected to increase in the upcoming century (IPCC, 2007), empirical modelling studies suggest that the rate of this increase could be insufficient to compensate for the warming (Flannigan *et al.*, 2005). Longer fire seasons and large expanses of forests and peatlands vulnerable to fire because of deeper seasonal thawing (Kasischke and Turetsky, 2006) could also lead to future area burned statistics located outside of the historical range as indicated by this statistical reconstruction of AAB. Extrapolation of the variability within the reconstruction for forecasting future area burned could hence be misleading. With the advent of dynamic climate–vegetation models (eg, Arora and Boer, 2005), the most plausible use of these data could take the form of a simulation-validation scheme, where simulations of fire activity response to past solar, volcanic, aerosols and greenhouse gas forcing would be compared with estimates of AAB (eg, Wilson *et al.*, 2006). This would help to determine sensitivities of fire activity to forcing and a range of confidence in long-term wildfire forecasts.

Conclusion

We presented the first extended, well-replicated, statistically verified, and long-duration reconstruction of annual area burned for northwestern North America. Although such estimates have previously been made at the Canadian countrywide scale (Girardin, 2007), these new estimates have the properties of having improved year-to-year resolution and of being strictly calibrated on fire data of northwestern regions (the former being calibrated on countrywide 1920–1982 fire data). Spatial correlation maps of land temperature and precipitation data provided an indication of the reliability of the reconstruction to approximate fire activity/climate variability in northwestern Canadian ecozones beyond the period of calibration. Singular spectrum analysis and analysis of variance suggested that AAB has significantly changed during the course of the past 150 years toward increasing variance. Recent decadal changes in area burned fitted well within an oscillatory mode centred on 26.7 years. Analyses of oceanic and atmospheric teleconnections (linkages between weather changes occurring in widely separated regions of the globe) using combinations of proxy climate records, climate observations and general circulation models might help to elucidate the oscillatory behaviour in AAB and causal effects for long-term changes in variance.

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Appendix 1

The equation used to calculate the RE can be expressed in terms of the $\hat{y}_i$ estimates and y_i predictand that are expressed as departures from the dependent period mean value:

$$RE = 1.0 - \sum_{i=1}^{n'} (y_i - \hat{y}_i)^2 \,/\, \sum_{i=1}^{n'} y_i^2 \tag{2}$$

The term to the right of Equation (2) is the ratio of the total squared error obtained with the regression estimates and the total squared error obtained using the dependent period mean as the only estimate. This average becomes a standard against which the regression estimation is compared. If the reconstruction does a better job than the average of the dependent period, then the total error of the regression estimate is less, the ratio is less than one and the RE is positive.

The PM test calculates the products of the deviations and collects the positive and negative products in two separate groups based on their signs. The values of the products in each group are summed, and the means computed. The difference between the absolute values of the two means $M_+ - M_-$ can be tested for significance using t statistics:

$$t = (M_+ - M_-)/(S_+^2/n_+ + S_-^2/n_-)^{1/2} \tag{3}$$

where n_+ and n_- are the number of positive and negative products and S_+^2 and S_-^2 are the corresponding variances.

Table A1 Sources of the site tree-ring width chronologies

Species	Contributors	Location	Lat.	Long.	Period
Picea glauca	D'Arrigo, R., Mashig, E., Frank, D., Wilson, R. & Jacoby, G.	Burnt Over	65.13	162.15	1621–2002
Picea glauca	Sauchyn, D.	Tibbitt Lake	62.32	133.21	1718–1998
Picea mariana	Sauchyn, D. & Beriault, A.	Grizzly Ridge, Mirror Lake	62.02	128.16	1703–2001
Picea mariana	Sauchyn, D. & Beriault, A.	Kuskula Creek, Mirror Lake	62.02	128.16	1666–2001
Picea glauca	Sauchyn, D., Beriault, A. & Stroich, J.	Sunblood Mountain	61.39	125.38	1699–2001
Pinus contorta	Sauchyn, D., Beriault, A. & Stroich, J.	Sunblood Mountain	61.39	125.38	1765–2001
Picea glauca	Sauchyn, D., Beriault, A. & Stroich, J.	Trout River	61.19	119.51	1757–2001
Picea glauca	Sauchyn, D.	Evelyn Falls	60.55	117.20	1750–2003
Picea glauca	Sauchyn, D.	Swan Hills-Swan River	54.45	115.37	1752–2004
Pinus banksiana	Sauchyn, D.	Swan Hills-Swan River	54.45	115.37	1733–2004
Picea glauca	Meko, D.	Birch River	58.30	112.30	1757–2000
Picea glauca	Meko, D., Stockton, C., Fritts, H. & Knowles, T.	Point Providence	59.00	112.00	1698–2000
Picea glauca	Meko, D.	Horseshoe Slough	58.54	111.36	1801–2000
Picea glauca	Meko, D., Stockton, C., Fritts, H. & Knowles, T.	Athabasca River	58.24	111.30	1708–2000
Picea glauca	Sauchyn, D.	Christie Bay	62.33	111.25	1629–2002
Picea glauca	Meko, D., Stockton, C., Fritts, H. & Knowles, T.	Revillon Coupe	58.54	111.24	1742–2000
Picea glauca	Meko, D., Stockton, C., Fritts, H. & Knowles, T.	Peace/Rouchers	59.00	111.24	1687–2000
Picea glauca	Meko, D.	Mamawi Lake	58.36	111.18	1801–2000
Picea glauca	Sauchyn, D. & Beriault, A.	Gray Lake, Taltson River	61.56	108.03	1776–2001
Pinus banksiana	Beriault, A., Sauchyn, D. & Stroich, J.	Fleming Island, Cree Lake	57.33	106.53	1767–2002
Pinus banksiana	Beriault, A., Sauchyn, D. & Stroich, J.	McGugan Island, Highrock Lake	57.04	105.30	1833–2002
Pinus banksiana	Beriault, A., Sauchyn, D. & Stroich, J.	Bolen Lake	57.51	103.50	1819–2002
Betula papyrifera	Tardif, J.	Duck Mountain Prov. Forest	51.60	101.00	1785–2001
Thuja occidentalis	Tardif, J.	Cedar Lake	53.00	99.16	1713–1999
Pinus resinosa	Tardif, J.	Black Island	51.10	96.30	1709–2001
Thuja occidentalis	Girardin, M.P.	Sleeping Giant Prov. Park	48.32	88.87	1665–2001
Picea mariana	Girardin, M.P.	Sleeping Giant Prov. Park	48.37	88.82	1676–2001
Thuja occidentalis	Girardin, M.P.	Beardmore	49.63	88.08	1677–2001
Thuja occidentalis	Girardin, M.P.	Rainbow Fall	48.50	87.38	1774–2001
Thuja occidentalis	Girardin, M.P.	Upper Twin Lake	50.15	86.55	1772–2001
Thuja occidentalis	Girardin, M.P.	Fushimi Lake	49.83	83.92	1765–2002
Picea mariana	Girardin, M.P.	René-Brunelle	49.42	82.13	1721–2002
Pinus banksiana	Girardin, M.P.	Blue Lake	48.58	81.72	1760–2002
Pinus strobus	Girardin, M.P.	Geiki Lake	48.18	81.08	1710–2002
Betula papyrifera	Charron, D. & Bergeron, Y.	Lac Duparquet	48.28	79.19	1766–1998
Picea mariana	Lesieur, D.	Réservoir Gouin	48.56	74.30	1775–1997
Pinus banksiana	Lesieur, D.	Réservoir Gouin	48.56	74.30	1767–1998
Picea mariana	Gauthier, S. & DeGranpré, L.	Lac Dionne	49.66	67.58	1743–1999

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