The Tree-Ring Record of Drought on the Canadian Prairies[a,b]

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ABSTRACT

Ring-width data from 138 sites in the Canadian Prairie Provinces and adjacent regions are used to estimate summer drought severity during the past several hundred years. The network was divided into five regional groups based on geography, tree species, and length of record: the eastern Rockies, northern Saskatchewan, central Manitoba, southern Manitoba, and northwestern Ontario. Regional tree-ring records are primarily related to summer moisture and drought conditions, and are less responsive to droughts caused by deficits in winter precipitation. These summer-sensitive data are not linearly related to major modes of climate variability, including ENSO and the Pacific decadal oscillation (PDO), which primarily affect the climate of western Canada during winter. Extended drought records inferred from tree rings indicate that drought on the Canadian Prairies has exhibited considerable spatial heterogeneity over the last several centuries. For northern Saskatchewan and northwestern Ontario, intervals of persistently low tree growth during the twentieth century were just as long as or longer than low-growth intervals in the eighteenth or nineteenth centuries. Longer records from southern Alberta suggest that the most intense dry spell in that area during the last 500 yr occurred during the 1720s. At the eastern side of the prairies, the longest dry event is centered around 1700 and may coincide with low lake stands in Manitoba, Minnesota, and North Dakota. Although the Canadian Prairies were dry at times during the 1500s, there is no regional analog to the sixteenth-century ‘‘megadroughts’’ that affected much of the western United States and northern Mexico.

1. Introduction

Most prior studies using tree-ring data to understand past drought in the Canadian Prairie Provinces have been based on either single chronologies (composite time series that represent mean growth within the stand of trees) from individual locations (e.g., Sauchyn and Beaudoin 1998; Sauchyn et al. 2003) or multiple chronologies from a relatively small area [100–200-km transects; e.g., Case and MacDonald (1995); St. George and Nielsen (2002); Girardin and Tardif (2005)]. This work has demonstrated that data from Prairie trees can be an effective proxy for meteorological or hydrological drought, and can be used to develop annually resolved drought records that extend back several hundred years (Watson and Luckman 2006, and references therein).

Despite these encouraging results, making inferences about the drought history of the entire Prairies (or even individual regions) from a limited number of records remains a challenge because tree-ring data often contain multiple signals (of varying strengths) created by different environmental forcings. Synoptic-scale climate

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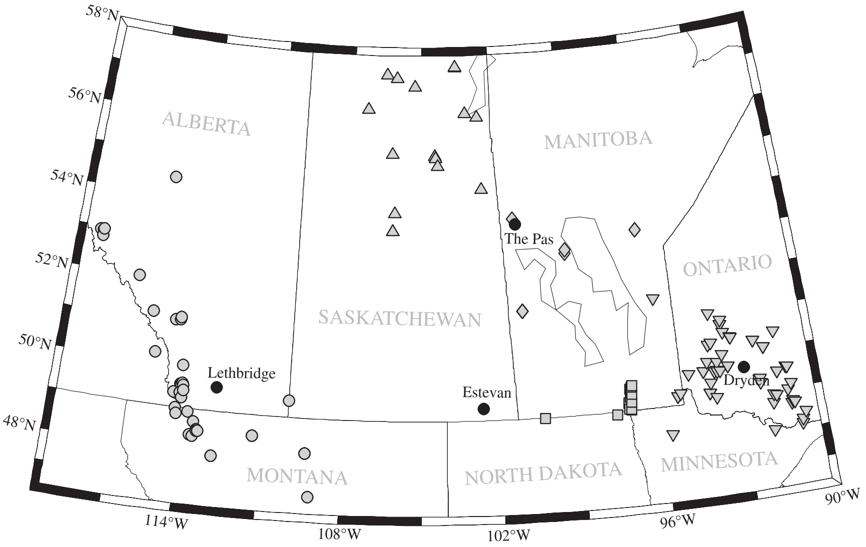


FIG. 1. Network of ring-width sites from the Canadian Prairies and adjacent regions. Symbols correspond to regional groups: eastern Rocky Mountains, circles; northern SK, upward triangles; central MB, diamonds; southern MB, squares; and northwestern ON, downward triangles. Black circles represent communities mentioned in the text.

is usually a major influence on ring width, but tree growth can also be influenced by disturbances (affecting both single trees and the entire stand) or the local microclimate (Cook 1985). Because it is not possible to separate these influences a priori, even ring-width chronologies developed from climate-sensitive trees can include nonclimatic signals. The problem of whether or not local proxy records can be taken as representative for the broader region is complicated further by the inherent spatial heterogeneity of drought; at a given time, severe drought conditions may be present over a small area, but it does not necessarily follow that the entire Prairies must also be affected by drought. Although many ring-width chronologies from this region have been incorporated into the *North American Drought Atlas* (Cook and Krusic 2004), attempts to extract regional signals from networks of moisture-sensitive trees in Canada have either focused primarily on drought in regions adjacent to (and, in some cases, overlapping with) the Canadian Prairie Provinces (Watson and Luckman 2004; Watson and Luckman 2005; Girardin et al. 2006b), or have targeted other environmental variables (e.g., area burned; Girardin 2007).

In this paper, we use 138 ring-width chronologies from the Canadian Prairie Provinces and adjacent regions (Fig. 1) to estimate changes in regional drought severity since approximately 1500 A.D. Many of these data are relatively new; almost all records have been developed since the mid-1990s, and nearly half were produced after the publication of the most recent version of the *North American Drought Atlas* (Cook and Krusic 2004). As noted by Cook and Krusic (2004), the number of moisture-sensitive ring-width chronologies in Canada has, until recently, been quite modest, and these new collections fill substantial gaps in the previous network. Using an extensive (greater than 2 000 000 km^2), relatively dense, network of chronologies allows us to focus our analysis on signals recorded by many or all records over large areas. These common signals are more likely to be related to synoptic-scale influences, including regional drought conditions, and should minimize contributions from local, nonclimatic noise. We describe the spatial and temporal variabilities of ring-width chronologies from the Canadian prairies, and examine the seasonality of moisture signals contained within regional tree-ring series. We also investigate potential connections between tree growth and a suite of major climate modes and discuss how the "climate window" (Fritts 1976) recorded by Prairie trees affects their ability to describe the influence of remote climate forcings. Finally, we examine what tree-ring data tell us about the intensity and persistence of drought during the past several hundred years as compared to drought observed during the period covered by instrumental records.

2. The Canadian Prairies

Most of the area in this study (approximately 47°–58°N and 90°–118°W) is part of the Prairie ecozone (Ecological Stratification Working Group 1996), a predominantly mixed-grass prairie with a semiarid climate and few trees. The prairie ecozone also coincides with the area commonly described as the Palliser Triangle, named after a nineteenth-century British expedition that mapped the territory between Lake Superior and the Pacific coast and assessed its potential for agriculture, mining, and settlement (Spry 1995). Most ring-width data used in this study are derived from trees growing along the margins of the prairie ecozone, including sites from the Montane Cordillera, Boreal Plains, and Boreal Shield ecozone (Ecological Stratification Working Group 1996). For simplicity, we refer to the broader region (shown in Fig. 1) as the Canadian Prairies or Prairies. This region also encompasses the drainage basin for the Nelson–Churchill River system, the third largest watershed in North America.

3. Tree-ring data

We assembled a set of regional ring-width data (Fig. 1; appendix A) from the International Tree-Ring Databank (information online at http://www.ncdc.noaa.gov/paleo/treering.html) and previously published material (Sauchyn and Beaudoin 1998; St. George and Nielsen 2002; Watson and Luckman 2002; Case and MacDonald 2003; Girardin and Tardif 2005; Beriault and Sauchyn 2006; Girardin et al. 2006b; Pederson et al. 2006; St. George et al. 2008). In many cases, these data were developed from trees under ecological conditions known to enhance the importance of moisture to tree growth [e.g., the forest–prairie border, sandy soils, or steep slopes; Fritts (1976); Meko et al. (1995)]. Prior studies have demonstrated that ring-width data from most of these sites exhibit some type of moisture signal, either related to seasonal or annual precipitation (Case and MacDonald 1995; Case 2000; Watson and Luckman 2001; Watson and Luckman 2002; St. George and Nielsen 2002; Sauchyn et al. 2003; St. George et al. 2008), summer drought (Sauchyn and Skinner 2001; Girardin and Tardif 2005; Girardin et al. 2006b; Pederson et al. 2006), area burned (Girardin et al. 2006a; Girardin 2007), or streamflow (Case and MacDonald 2003; Beriault and Sauchyn 2006; Watson and Luckman 2006). The tree-ring network can be divided into five regional groups based on geography, tree species, and length of record: (i) the eastern Rockies {primarily Douglas fir [*Pseudotsuga menziesii* subsp. *glauca* (Murray)] and limber pine [*Pinus flexilus* (James)] from lower-elevation sites in Alberta and Montana}, (ii) northern Saskatchewan {boreal forest trees, mainly white spruce [*Picea glauca* (Moench) Voss] and jack pine [*Pinus banksiana* Lamb.]}, (iii) central Manitoba [eastern white cedar (*Thuja occidentalis* L.) and a mixture of other species], (iv) southern Manitoba {bur oak [*Quercus macrocarpa* (Michx.)] from riparian forests}, and (v) northwestern Ontario [mainly red pine (*Pinus resinosa* Sol. ex Aiton) and white pine (*Pinus strobus* L.)]. The total network includes measurements of nearly 5000 samples taken from almost 3000 trees. Because of a number of factors (including the scarcity of trees in grassland ecosystems, frequent fires in the boreal forest, wet conditions that encourage heartrot, and intensive logging), the region contains relatively few long-lived trees. Although trees in the foothills of the Rockies can be quite old (the oldest tree, from the Teton River valley in Montana, has 846 rings), the median age of trees in the network is only 135 yr.

4. Instrumental climate data

Precipitation data for the Canadian Prairie region were extracted from the Climatic Research Unit (CRU) TS 2.1 gridded (0.5°) dataset of monthly climate observations (Mitchell and Jones 2005) and combined into annual (October–September) and seasonal (December–February, DJF; March–April, MAM; June–August, JJA and September–November, SON) totals. We also used gridded Palmer drought severity index (PDSI) records from the dataset developed by Dai et al. (2004), but we truncated these records at 1900 because of the scarcity of climate stations on the Canadian Prairies prior to the twentieth century. Some analyses were repeated using the Cook et al. (2004a) gridded set of instrumental PDSI data for North America but we did not note any major differences in our results. All of these gridded products are produced from individual station records, and because of the lack of high quality, long-term climate stations in many parts of northern Canada, it is necessary to be cautious when interpreting potential climate signals in the northern Prairies.

Climate indices for several major modes of climate variability, including the Atlantic multidecadal oscillation (AMO), Pacific decadal oscillation (PDO), the cold tongue index (CTI), the Pacific–North America teleconnection pattern (PNA), and the northern annular mode (NAM), were downloaded from the Joint Institute for the Study of the Atmosphere and Ocean Web site (information online at http://jisao.washington.edu) and the National Oceanic and Atmospheric Administration (information online at http://www.cdc.noaa.gov), and averaged to produce either annual (AMO only) or cold season (October–March) means.

5. Analytical procedures

Ring-width measurements were detrended and combined to produce "standard" and "residual" (prewhitened) chronologies (Cook 1985; Cook et al. 1990) for each site. We attempted to emphasize signals that are common to many or all chronologies within each region (which are likely related to synoptic-scale influences like regional climate), and diminish signals that are present at only a few sites (which are probably caused by local factors like microclimatic differences or ecological disturbances). We used either empirical orthogonal function (EOF) analysis (North et al. 1982; Peixoto and Oort 1992) or simple averaging to identify the dominant mode of variability present in each region (i.e., the leading EOF or the regional mean) and construct summary series that represent regional tree growth (''regional tree-ring records''). A more complete description of the methods used to produce the ring-width chronologies and regional tree-ring records, including a discussion of standardization techniques, signal strength statistics, and our EOF approach, is provided later (see appendix C).

Potential climate signals in regional tree growth were evaluated by comparing individual ring-width chronologies and the regional tree-ring records with (i) gridded climate products and (ii) indices of major modes of climate variability that might plausibly influence the Canadian prairies. All significance tests for correlation were adjusted for the loss of degrees of freedom associated with autocorrelated time series (Dawdy and Matalas 1964). Cross-spectral analysis was conducted using Welch's averaged periodogram method (MathWorks 2007; Trauth 2006). Significance levels for coherence (squared) were computed by a Monte Carlo procedure: 10 000 series with the same spectral properties as the regional tree-ring records were generated by exact simulation (Percival and Constantine 2006), and were subjected to cross-spectral analysis to establish empirical confidence levels.

6. Results

a. Ring-width chronologies

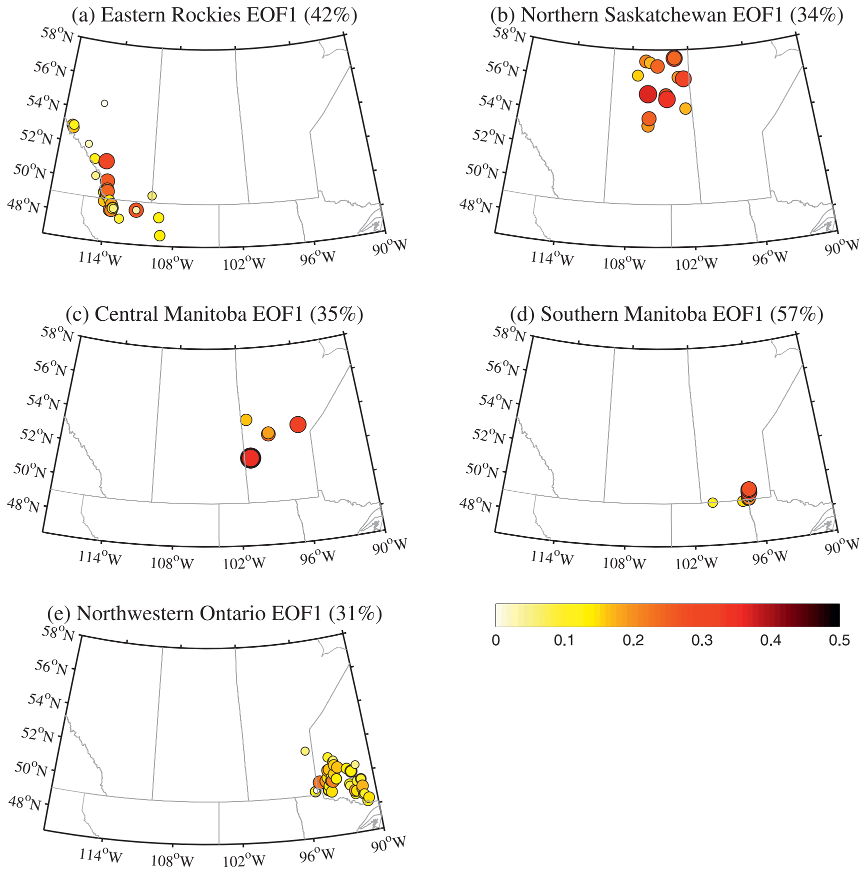
Most ring-width chronologies (60%) describe at least 85% of their stand-wide signal (Wigley et al. 1984; appendixes B and C) back until 1850 A.D., but there is a rapid dropoff thereafter. Only 30 chronologies retain their signal to 1700 A.D., only 15 to 1600 A.D., and only 7 (all from the eastern Rockies) contain a robust signal prior to 1500 A.D. Only the leading eigenvectors (EOF1) from each region were retained for subsequent analysis; effectively, these eigenvectors (Fig. 2) describe the common regional signal that allows tree-ring patterns to be matched between sites several hundred kilometers apart. Because the set of tree-ring sites from central Manitoba includes a small number of chronologies (10) that are weakly correlated with each other, we were not able to define a meaningful summary series to represent tree growth in this region.

b. Climate signals in prairie tree rings

In general, regional tree-ring records from the Prairies are correlated with summer (JJA) precipitation over a broad area surrounding the sites used to define each regional pattern (Fig. 3). With the exception of the data from northern Saskatchewan, the regional tree-ring records developed from standard ring-width chronologies were more highly correlated with regional precipitation (and PDSI) than those developed from residual chronologies. Several regional series (eastern Rockies, southern Manitoba, and northwestern Ontario) are correlated with precipitation records from grid points more than 500 km away from the tree-ring sites. The leading pattern for northern Saskatchewan shows the weakest connection to summer precipitation and, instead, has higher and more extensive correlations with spring (primarily May) precipitation in central Saskatchewan (see Fig. S4 in the supplementary material for this paper). The tree-ring records for southern Manitoba and the eastern Rockies are also correlated with spring precipitation, but for the most part, these correlations are weaker and extend over a smaller area than those obtained using summer precipitation. None of the regional tree-ring series are significantly correlated with precipitation during the prior autumn or winter (see Figs. S1–S4 in the supplementary material). The regional series also correlate with annual precipitation, but this correspondence likely reflects the importance of summer rainfall on the Prairies rather than a real physical relationship between ring width and precipitation over the entire year (see the section 7).

Regional tree-ring records are also correlated with July PDSI over large parts of the Prairies (Fig. 4). Tree growth in southern Manitoba and the eastern Rockies appears to record the most widespread drought signals, with both series showing significant correlations over the entire southern prairies and adjacent American states. In general, the regional series are mostly highly correlated with PDSI records from nearby grid points, which likely reflects the direct connection between tree growth and local drought conditions. The series for northern Saskatchewan and southern Manitoba are most highly correlated with drought records one or two grid points away; these offsets are probably artifacts created by interpolating the gridded climate data from a sparse network of stations.

We identified those grid points whose PDSI records have the highest absolute correlation with the regional



(a) Eastern Rockies EOF1 (42%)

(b) Northern Saskatchewan EOF1 (34%)

(c) Central Manitoba EOF1 (35%)

(d) Southern Manitoba EOF1 (57%)

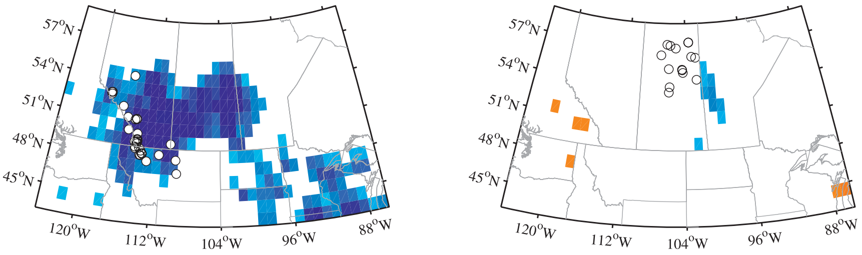
(e) Northwestern Ontario EOF1 (31%)

FIG. 2. Eigenvector loadings for EOF analysis of regional ring-width groups: (a) eastern Rocky Mountains EOF1 (standard chronologies), (b) northern SK EOF1 (residual chronologies), (c) central MB EOF1 (standard chronologies), (d) southern MB EOF1 (standard chronologies), and (e) northwestern ON EOF1 (standard chronologies). The values in parentheses indicate the amount of variance described by each pattern relative to the total in each regional network. The period of analysis is 1900–2004. The area of the circle is proportional to the eigenvector loadings for each chronology.

tree-ring records (marked by red squares in Fig. 4), and compared the PDSI and ring-width time series (Fig. 5). The PDSI grid points are named after nearby communities: Lethbridge, Alberta; The Pas, Manitoba; Estevan, Saskatchewan; and Dryden, Ontario. The regional series tracks PDSI most closely for the eastern Rockies–Lethbridge ($r = 0.62$, $p < 0.0001$) and southern Manitoba–Estevan ($r = 0.52$, $p < 0.0001$). Tracking is weakest in northern Saskatchewan ($r = 0.26$, $p < 0.02$), possibly because trees in this region are less limited by moisture and less sensitive to drought, but it may also reflect problems with instrumental PDSI records related to the paucity of long-term climate stations in this area (New et al. 2000).

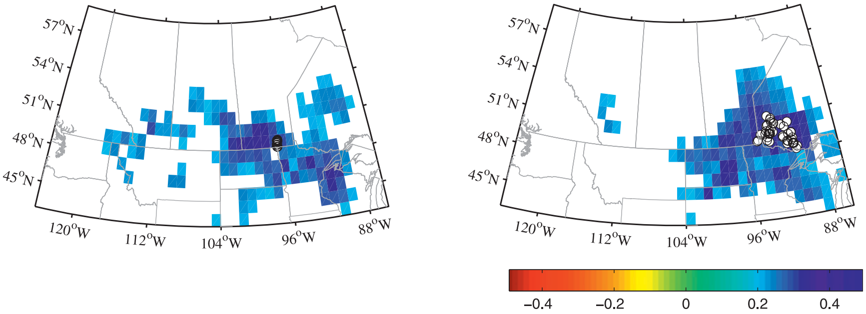
The relationship between PDSI and tree growth appears to be frequency dependant. Both PDSI and tree-ring series have predominantly low-frequency spectra (Table 1) and two of the four tree-ring–PDSI pairs (eastern Rockies–Lethbridge and southern Manitoba–Estevan) show greater coherence at low frequencies (Fig. 6). For the eastern Rockies, coherence is significant (0.05 level) at wavelengths longer than about 5 yr. For the southern Manitoba–Estevan pair, coherence is higher (but not statistically significant) above 10 yr and significant ($p = 0.05$) around 3 yr. Tree-ring and PDSI records from northwestern Ontario show a strong peak in coherence around 2–3 yr, and a second, less significant, peak around 10 yr. Cross-spectral results for northern Saskatchewan confirm that these trees contain a relatively weak PDSI signal: peaks in coherence are found near 3 and 10 yr but neither reaches significance at the 0.05 level.

For the most part, individual chronologies display the same sensitivity to summer precipitation as the regional tree-ring series: more than half of all chronologies (82) show significant and spatially extensive correlations



(a) Eastern Rockies PC1

(b) Northern Saskatchewan PC1



(c) Southern Manitoba Mean

(d) Northwestern Ontario PC1

FIG. 3. Correlations between major patterns of regional tree-ring width and gridded summer (JJA) precipitation, calculated for the 1901–2004 interval. Only correlations that are significant at the 0.05 level are shown. The white circles mark the tree-ring chronologies used to define each regional pattern.

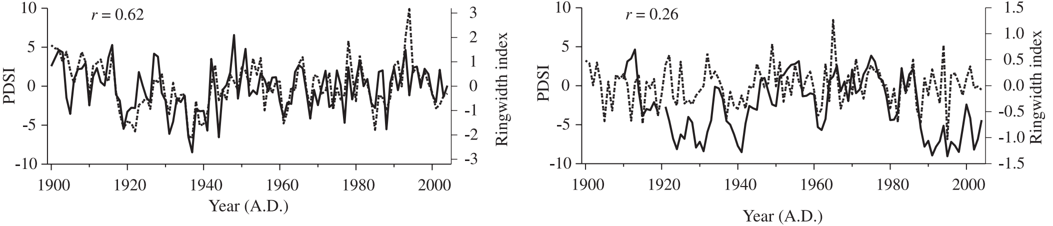
with summer precipitation. A smaller number of chronologies (25) are significantly correlated with spring precipitation, and six records, almost all from the eastern Rockies, show an apparent signal related to the amount of snow in winter. Some individual chronologies are more highly correlated with July PDSI than the corresponding regional tree-ring series. In northern Saskatchewan, seven chronologies (out of 16) are more highly correlated with July PDSI at The Pas than the regional tree-ring series. In northwestern Ontario, 10 chronologies (out of 55) are more highly correlated with PSDI than the regional tree-ring series. This tendency is not present in southern Manitoba, where the highest correlation between an individual chronology and PDSI is equivalent to the correlation between PDSI and the regional tree-ring series. It is also absent in the western Prairies; none of the ring-width chronologies from the eastern Rockies are as highly correlated with the Lethbridge PDSI record as the regional tree-ring series.

c. Associations with major climate modes

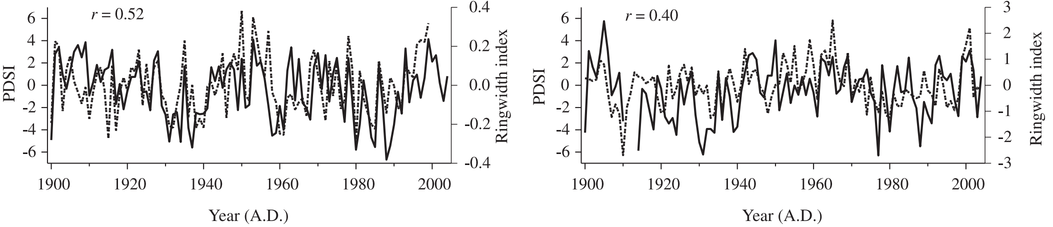
Mapping the correlation between individual ring-width chronologies and major climate indices shows that ring width across the region is not associated with either the CTI (a measure of ENSO) or the PNA pattern (Fig. 7). The other three indices have a greater number of significant correlations, but for the most part they do not create the coherent spatial fingerprint that would be expected if these modes had a real influence on prairie trees. For example, the PDO is significantly correlated with just five chronologies in the eastern Rockies, and the sign of the correlation is not consistent among these records. Because trees in the eastern Rockies exhibit a strong regional signal and should respond similarly to a synoptic-scale climate forcing, it seems likely that these correlations with the PDO are spurious. Several chronologies from northwestern Ontario are significantly correlated with the AMO, the PDO, and the NAM, but again, these correlations are not present at all sites in the region. The apparent correspondence between the AMO and tree growth in northwestern Ontario is difficult to reconcile with prior analysis of instrumental records, which has shown that the AMO does not affect drought in this part of Canada (Shabbar and Skinner 2004). Finally, none of the regional tree-ring records are significantly correlated with any of the five climate indices (not shown).

d. Tree-ring estimates of past drought

The above results demonstrate that ring-width chronologies from the Canadian Prairies contain regionally coherent signals (with the exception of chronologies from central Manitoba), and that these signals are associated with summer moisture (June–August precipitation) or


(a) Eastern Rockies PC1 - 'Lethbridge'

(b) Northern Saskatchewan PC1 - 'The Pas'


(c) Southern Manitoba mean - 'Estevan'

(d) Northwestern Ontario PC1 - 'Dryden'

TABLE 1. Fraction of variance at low frequencies (≥5 yr) in regional ring-width and PDSI series.

Region	Ring width	PDSI
Eastern Rockies	0.6931	0.5633
Northern SK	0.3622	0.9086
Southern MB	0.4909	0.6023
Northwestern ON	0.6493	0.6294

most effectively modeled as a simple linear transformation of its corresponding regional tree-ring records (from Fig. 5).

In light of the weak statistical relationships between ring width and PDSI, we chose to interpret the regional tree-ring record as qualitative measures of past drought severity (Fig. 8). Each regional series was scaled so that, during the period covered by instrumental drought records (1900–2004), its mean was equal to zero and its standard deviation was equal to one. This approach is effectively a simplified version of the composite-plus-scale technique (Jones and Mann 2004; Esper et al. 2005). The regional series were also smoothed with a 5-yr Gaussian filter to emphasize longer-term variability that, at least in some regions, is more closely tied to similar behavior in the instrumental PDSI records. The terminology used to describe the inferred drought records is modeled after Biondi et al. (2002); *duration* is the number of consecutive years the series remains above or below the instrumental period mean, and *intensity* is the average departure from the mean for a given duration.

1) EASTERN ROCKIES

The tree-ring record from southern Alberta and northern Montana suggests that at least one drought during the last 500 yr was more intense than droughts observed in the instrumental record. The first attempts to derive drought history using tree rings from this region were based on a limited number of ring-width chronologies and suggested that the 1790s was the driest decade in southern Alberta in the last several hundred years (Case and MacDonald 1995; Sauchyn and Beaudoin 1998; Wolfe et al. 2001). Our much larger dataset indicates that tree growth was exceptionally low in the 1790s at only a few sites (most prominently, the Towers Ridge site near Calgary, Alberta). The regional series suggests that the most intense drought in southern Alberta since 1500 A.D. occurred in the early 1720s. The most extreme low-growth year in the eastern Rockies record (1720) also falls within this interval. The dry spells with the greatest duration occurred in the early twentieth century (1918–42) and the middle of the nineteenth century

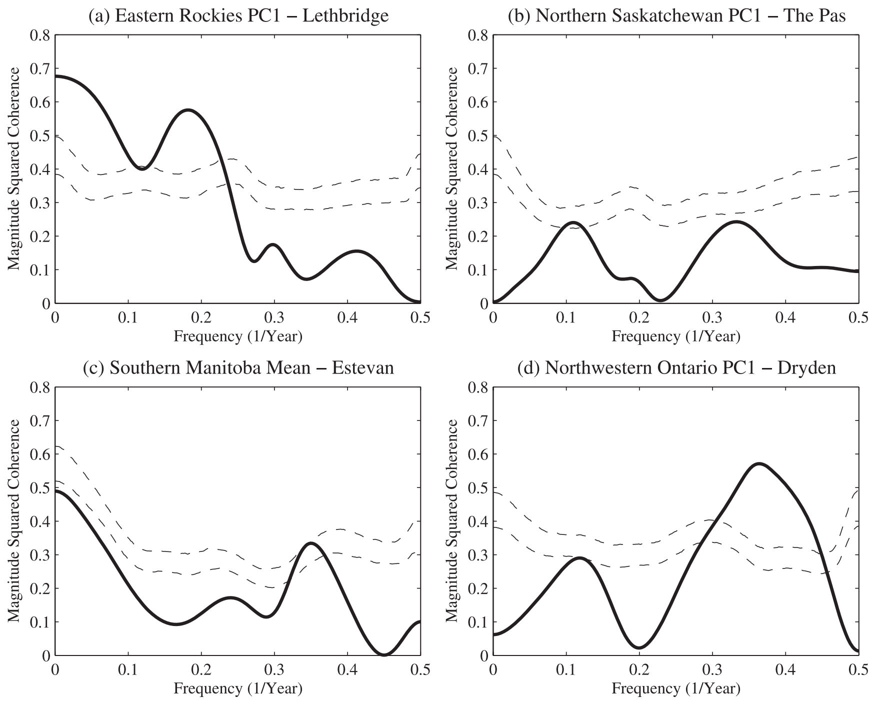
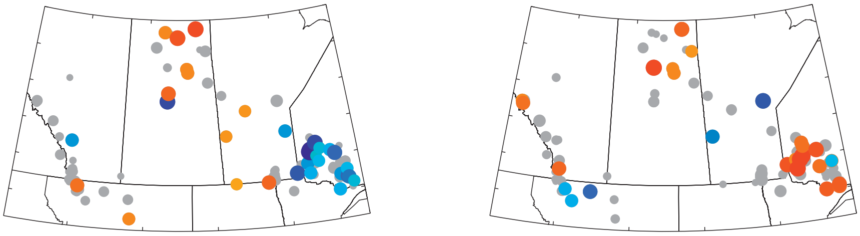
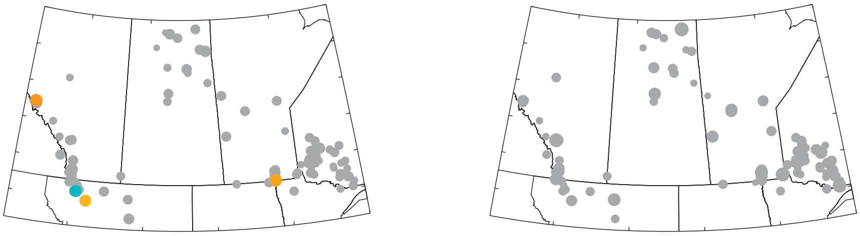


FIG. 6. Coherence between regional ring-width and PDSI records. The 90% and 95% confidence levels are represented by the dashed lines and were determined by a Monte Carlo approach that generated 10 000 random series with the same spectral properties as the original time series: (a) eastern Rockies PC1, (b) northern Saskatchewan PC1, (c) southern Manitoba mean, and (d) northwestern Ontario PC1.



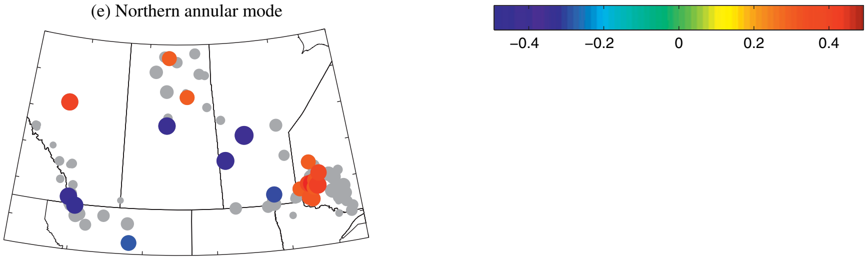
(a) Atlantic Multidecadal Oscillation

(b) Pacific Decadal Oscillation



(c) Cold Tongue Index

(d) Pacific North America Pattern



(e) Northern annular mode

FIG. 7. Correlations between ring-width chronologies on the Canadian Prairies and major climate modes. Colored circles show correlations significant at the 0.05 level, after the adjustment for temporal autocorrelation. The area of the circle is proportional to the correlation coefficient for each chronology: (a) AMO, (b) PDO, (c) CTI, (d) PNAP, and (e) NAM.

(1842–77). The earlier drought coincides with the Palliser expedition of 1858–59, which reported sparse rains, dry river beds, and arid country throughout southern Alberta and Saskatchewan (Spry 1995; Rannie 2006). The tree-ring evidence suggests that southern Alberta had already been dry for a decade and a half at the time of Palliser's expedition, and would remain so until the late 1870s. This interval also encompasses the ''Civil War Drought'' (1856–65) identified in the central United States (Herweijer et al. 2006), but it does not seem that droughts in both regions can be attributed to the same climate forcing. Herweijer et al. (2006) argued that the prolonged drought in the U.S. Great Plains was driven by the La Niña–like tropical Pacific, but because this configuration generally brings more moisture to western Canada (Shabbar et al. 1997; Bonsal and Lawford 1999), this mechanism cannot account for dry summer weather in the eastern Rockies at the same time. Finally, the first two decades of the twentieth century appear to have been one of most prolonged wet periods in the entire record, lending support to the argument that first major pulse of Euro-Canadian settlement in the western prairies occurred during unusually favorable climate conditions (Sauchyn and Beaudoin 1998; Watson and Luckman 2006). This period also coincided with the early twentieth-century pluvial observed in the western United States (Woodhouse et al. 2006; Pederson et al. 2006), and unusually high flows in the Colorado River (Meko et al. 2007). The early 1800s is the only other wet period of comparable duration; this pluvial included exceptionally high tree growth at sites across the region in 1839.

2) NORTHERN SASKATCHEWAN

Tree-ring data from northern Saskatchewan identify persistent dry conditions in the late 1880s, early 1900s, and circa 1940. The last period is coincident with the lowest recorded flow in the Churchill River (Beriault and

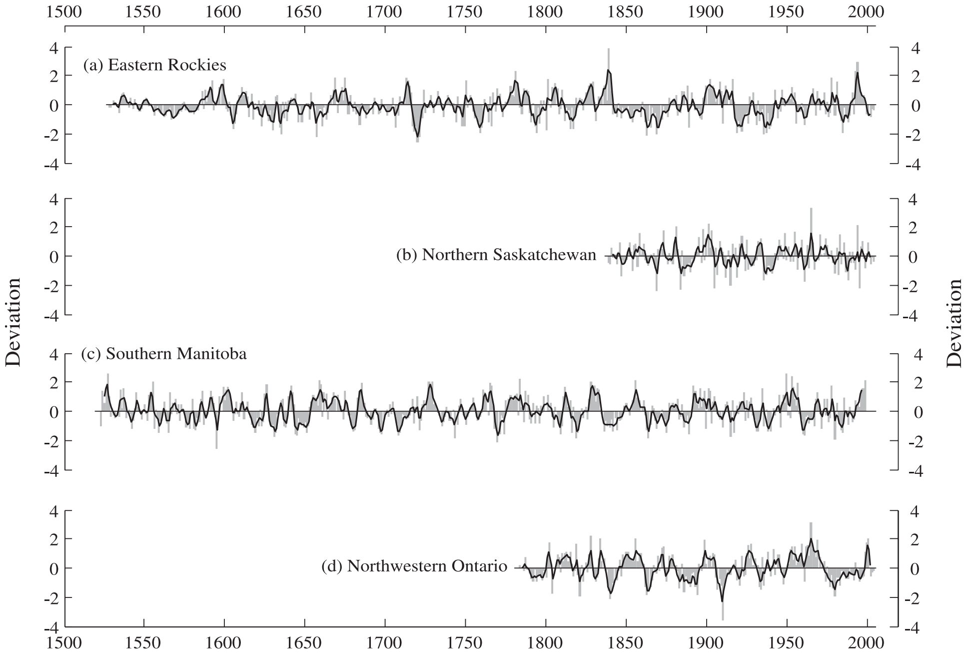


FIG. 8. The tree-ring record of drought in the Canadian Prairies. Each series is scaled to have a zero mean and equal variance during the instrumental period (1900–2004). The heavy line illustrates variability on time scales >5 yr.

Sauchyn 2006), which drains a large portion of northern Manitoba and Saskatchewan. Low growth across northern Saskatchewan during 1869 coincided with poor growth in the eastern Rockies, southern Manitoba, and the western half of the northwestern Ontario network; several prior studies have noted that drought was widespread across most of western Canada in this year (Watson and Luckman 2005; Cook and Krusic 2004). As in southern Alberta, this area appears to have experienced persistent wet conditions at the beginning of the twentieth century.

3) SOUTHERN MANITOBA

The most prominent feature of the inferred drought record for southern Manitoba and southeastern Saskatchewan is a prolonged absence of wet years around 1700. Between 1688 and 1715, growth was above the instrumental period mean for only 5 yr out of 28. An earlier analysis of the southern Manitoba tree-ring record using a different standardization technique (regional curve standardization) also indicated that this region was dry for several decades circa 1700 (St. George and Nielsen 2002). Radiocarbon dates of drowned trees on the margin of Lake Winnipeg suggest that the lake was lower by roughly 1 m around 1650 A.D. (Nielsen 1998). Given the limitations of radiocarbon dating within the last 200–300 yr (Stuiver and Reimer 1993), it is possible that lowered lake levels coincided with prolonged drought upstream in southern Manitoba. A composite flood history for the Red River in southern Manitoba was developed from gauge records, historical observations, and anatomical signatures in riparian trees and records major floods in 1747, 1762, 1826, 1852, 1862, 1950, and 1997 (St. George and Nielsen 2003). Except for 1747, these floods occurred during periods of persistent above-average wet conditions inferred from the regional tree-ring record.

4) NORTHWESTERN ONTARIO

The regional tree-ring series for northwestern Ontario indicates that the most extreme and prolonged drought conditions occurred during the twentieth century. The duration of recent dryness (most prominently from 1906 to 1915 and 1974 to 1999) is unmatched in the earlier part of the record. The extreme low growth exhibited by regional trees in 1910 is well beyond any of the other negative growth anomalies that have occurred since 1783. This observation led us to conclude that summer drought in northwestern Ontario in the twentieth century was more extreme than drought in the nineteenth and late eighteenth centuries. Twentieth-century wetness appears to be similarly exceptional. Between 1951 and 1972, regional tree growth was above the mean for 20 yr out of 23, including the record's peak growth year of 1965.

7. Discussion

Our results demonstrate that ring-width data from the Canadian Prairies primarily describe signals related to moisture and drought conditions during summer. In some cases, regional tree-ring records are correlated with summer precipitation and drought records several hundred kilometers distant. Fritts (1976) introduced the concept of the ''climatic window,'' whereby certain climatic ''inputs'' pass through the physiological system of a tree and are converted into a certain ring-width ''output.'' Within this framework, the tree can be thought of as a filter that emphasizes some climatic signals and minimizes others. This idea can be extended to include the behavior of the climate system as well: aspects of the climate system that are highly variable are more likely to create stronger signals in tree-ring series than those that are relatively static. The seasonality (or climate window) of Prairie tree-ring records has important implications for their interpretation as drought proxies.

First, the sensitivity of Prairie tree rings to summer moisture serves to limit their connection to major climate modes. The impact of ENSO and the PDO on precipitation over southern Canada is strongest during winter and is dampened out by the following spring (Shabbar et al. 1997; Mantua and Hare 2002). Several authors have noted that summer drought on the Prairies is statistically associated with wintertime ENSO conditions 1–2 yr prior (Bonsal et al. 1993; Bonsal and Lawford 1999; Shabbar and Skinner 2004), but, although Prairie trees are primarily sensitive to summer drought, there is no apparent association between regional tree-ring records and either ENSO or the PDO. We infer that (i) Prairie trees are largely insensitive to the stronger winter precipitation signals created by either ENSO or the PDO and (ii) any summertime ENSO signal is too weak to be detected using tree-ring records.

Second, the absence of a winter moisture signal at nearly all sites is the most likely reason why tree rings do not exhibit a pronounced negative anomaly associated with the recent 2000–01 drought, which has been described as the most intense drought in the western prairies during the last 100 yr (Sauchyn et al. 2003; Liu et al. 2004). Although the summer was also dry, the 2000–01 drought was caused primarily by a deficit in winter precipitation (Liu et al. 2004), which, because of its timing, had a limited impact on regional tree growth. Trees at sites in the eastern Rockies region formed narrow rings in 2001 but overall, tree-ring records from this area were not as low as during other twentieth-century droughts, such as 1936–37 or 1961.

Finally, the importance of summer rainfall to the Canadian Prairies creates an association between regional tree growth and total annual precipitation. Several prior studies have used ring-width chronologies from the Prairies to reconstruct annual precipitation (e.g., Case and MacDonald 1995; Sauchyn and Beaudoin 1998; St. George and Nielsen 2002; Watson and Luckman 2005). Our results suggest that, at the regional scale, the correspondence between prairie tree rings and annual precipitation may reflect a statistical association driven by a true causal relationship with summer precipitation. Although tree-ring records are, for some regions, significantly correlated with spring precipitation (especially in northern Saskatchewan), they are not significantly related to precipitation during the prior autumn or winter. If these data contained a true annual signal integrating precipitation over the entire year, they should correlate with precipitation during all seasons, not just summer. Instead, the association between all four regional tree-ring series and the annual precipitation is likely an artifact created by the prominence of summer rainfall in this part of Canada. The precipitation regime of the Prairies is summer dominant (Borchert 1950; Bonsal et al. 1999); that is, summer is the wettest season, and summer rainfall is more variable and more highly correlated with annual totals than precipitation during the other seasons. As a consequence, any proxy record that is strongly influenced by summer rainfall will also track annual precipitation, even if that record is not sensitive to precipitation anomalies during the other three seasons. Because summer rainfall and the total annual precipitation are so similar, regional ring-width records can be used to infer the past variability of either variable; however, it should be considered that such inferences depend primarily on signals created by summer conditions.

In some regions, it may be possible to develop better drought reconstructions (i.e., explain more variance) by using a subset of ring-width chronologies rather than all ring-width chronologies within a region. Dendroclimatic studies often use screening procedures to identify chronologies that are correlated with a specific climate variable and use those chronologies (only) as the basis for subsequent analysis (e.g., Cook et al. 1999; Meko et al. 2001; Woodhouse et al. 2006). This approach is best suited for tree-ring networks that contain chronologies that are either uncorrelated with climate or are sensitive to a different aspect of climate than the rest of the set. This alterative may be viable in northern Saskatchewan and northwestern Ontario, as both networks include several chronologies that are more similar to PDSI than their regional tree-ring series. If regional tree-ring series were built using only those chronologies that are highly correlated with PDSI, it may be possible to obtain a more ''pure'' drought signal and produce a statistically superior regression model. The main weakness of this method is the attendant decrease in sample size: the resulting reconstruction would be derived from fewer trees and would be potentially more vulnerable to the effect of nonclimatic influences. Our results suggest that drought estimates for the eastern Rockies or southern Manitoba would not be improved by some type of screening procedure. For both areas, the regional tree-ring series appears to be a better proxy of PDSI than any of its component ring-width chronologies. However, screening may help isolate ring-width variability that reflects the influence of winter precipitation. A small number of chronologies in the eastern Rockies (particularly Pyramid Lake, Lake Annette, Maligne Canyon, Teton River Valley Douglas fir, and Bears Paw Mountains Douglas fir) are significantly correlated with winter precipitation, but this behavior is present at too few sites to be resolved by the EOF analysis. The apparent sensitivity of these sites to winter precipitation may be due to random chance, but might also reflect a real but subtle signal that is poorly characterized by the current ring-width network. More records in the eastern Rockies are needed to determine if this association describes a real relationship and to identify the site characteristics that make some trees at the lower-forest border sensitive to winter conditions.

Tree-ring evidence suggests that the drought on the Canadian Prairies has exhibited considerable spatial heterogeneity over the last 500 yr, and it is rarely appropriate to describe the entire region as being either wet or dry. Although the two longest inferred drought records (the eastern Rockies and southern Manitoba) are significantly correlated ($r = 0.2$, $p = 0.00001$), there are several examples when one region was in drought and the other was not. The 1720s drought, which was extremely intense in the west, does not appear to have affected the eastern prairies, which was itself just recovering from a prolonged drought circa 1700 that went unrecorded in the west. Most parts of the prairies were dry at some time during the 1850s and 1860s, but this mid-nineteenth-century drought lasted the longest in southern Alberta and northern Montana. The lack of regional coherence in the tree-ring records is likely a product of the nature of summer precipitation on the Prairies. Although cyclonic and frontal activity plays a role in summer precipitation, rainfall is predominately convective and has high spatial variability (Raddatz 2005). Consequently, the spatial variability in the Prairie climate creates similarly variable (and localized) signals in the regional tree-ring network. The examples of contrasting drought conditions in the eastern and western sectors imply that the mechanisms that control persistent summer drought in each region are largely independent, at least those that operate at longer time scales, and corroborate Rannie (2006)'s warning against making general statements about drought on the entire Prairies based on proxy evidence from only one region.

We make a pair of observations on the potential connections between inferred drought in the Prairies and climate events at the continental or global scale. First, although the Canadian Prairies were dry at times during the 1500s, there is no regional analog to the sixteenth-century ''megadroughts'' that affected much of the western United States and northern Mexico (Stahle et al. 2000). Stahle et al. (2000) hypothesized that this widespread drought may have been caused by persistent cool water in the eastern equatorial Pacific (La Niña conditions). The Canadian prairies might be expected to be wet under those conditions, as modern La Niñas are associated with stronger westerlies moving across the eastern North Pacific and enhanced moisture delivery to western Canada during winter (Shabbar et al. 1997; Bonsal and Lawford 1999). Indeed, the eastern Rockies were wet throughout the 1590s, and although the region was dry for several years in the mid- to late 1500s (between 1555 and 1585), this episode does not appear as a prominent drought in this record. The southern Manitoba record also does not show any notable dry intervals during the sixteenth century, with the exception of 1595, the year of the lowest growth in that record. Second, the Prairies were not consistently wet or dry during the putative ''Little Ice Age'' [1570–1900 A.D.; Matthews and Briffa (2005)]. Tree-ring records exhibit considerable spatial and temporal variabilities during this period and include evidence of both wet and dry intervals. These data suggest that it is not appropriate to conceptualize the Little Ice Age on the prairies as a uniform, prolonged wet (or dry) anomaly extending over the entire region.

Does the instrumental period describe the complete range of drought variability on the Canadian Prairies during the last few hundred years? The answer to that question varies by region, and depends on how far back in time the tree-ring records allow us to look. For the cooler, wetter parts of the Prairies (northern Saskatchewan and northwestern Ontario), drought histories inferred from tree rings are only available for the last 150–200 yr. These records show that, during the twentieth century, intervals of persistently low tree growth were just as long as or longer than low-growth intervals in the eighteenth or nineteenth centuries. From this, we infer that instrumental climate records provide a reasonable approximation of the maximum duration of summer drought in these regions since circa 1800 A.D. The longer perspective afforded by tree-ring records in southern Manitoba and the eastern Rockies presents a different picture. The mid-nineteenth-century drought in southern Alberta and northern Montana had a greater duration than did the drought during the early twentieth century. The 1720s drought was not as long lasting, but was the most intense dry spell in the western Prairies in the last 500 yr. On the eastern side of the Prairies, the most notable dry event was centered around 1700 A.D. and persisted for almost three decades. Because of the limitations of radiocarbon dating, we cannot make unequivocal comparisons between the 1700 dry period in the eastern Prairies and the dry conditions inferred from geological evidence and most (nonvarved) limnological records in the region. Nonetheless, we do note that it is certainly possible that prolonged drought in southern Manitoba coincided with low stands in small lakes from Minnesota and North Dakota (St. George and Nielsen 2002), and low water levels in Lake Winnipeg (Nielsen 1998). In at least these two regions then, tree-ring evidence indicates that droughts that occurred within the last 300 yr were more intense and more persistent than those observed during the period covered by instrumental records.

8. Concluding remarks

The regional drought histories developed in this study may differ from earlier tree-ring reconstructions in some of the details, but the overall message remains largely the same. Tree-ring evidence indicates that parts of the Canadian Prairies have, relatively recently, been affected by summer droughts that were more intense and more long lasting that those observed in instrumental records. If similar droughts occurred in the future, it is not clear what impacts they would have on activities that rely heavily on inputs from summer moisture, such as agriculture, hydropower, or consumptive supplies. It may be prudent to examine the resilience of these systems to alternate worst-case scenarios based on these regional drought records inferred from tree rings. This exercise may be particularly important for the dryland areas of the western Prairie Provinces, which in the last few decades have experienced rapid population growth and agricultural expansion and concomitant increases in regional water demand (Schindler and Donahue 2006).

What aspects of the broader climate system have influenced prairie drought patterns during the last several centuries? The answer to this question remains uncertain, particularly because drought records derived from tree rings show relatively modest regional synchrony during the last several centuries. This apparent spatial heterogeneity suggests that persistent summer drought is principally related to regional- or local-scale forcings, rather than being driven by a single, synoptic-scale control that entrains drought conditions over the entire Canadian Prairies. Furthermore, although several studies have linked preinstrumental droughts in the United States to persistent La Niña conditions (Stahle et al. 2000; Herweijer et al. 2006), prairie droughts cannot be attributed to the same cause because western Canada occupies the opposite node of the precipitation dipole associated with ENSO.

It is important to recognize that conventional tree-ring records from the Canadian Prairies are somewhat limited in their application as proxies for past hydroclimatic conditions. Despite the addition of several dozen new chronologies, the regional tree-ring series are still a relatively poor basis for developing quantitative estimates of precipitation or drought severity, at least in comparison to tree-ring data from other parts of North America. Adding more ring-width chronologies might produce better results, but it might be more productive to supplement the existing ring-width network with records of other tree-ring parameters, such as earlywood–latewood width (Meko and Baisan 2001; Watson and Luckman 2002), wood density (Rigling et al. 2001), or isotopic composition (Leavitt et al. 2002; Masson-Delmotte et al. 2005). Multiproxy tree-ring studies in the southern French Alps (Gagen et al. 2004, 2006) indicate that drought reconstructions based on multiple tree-ring parameters may be more accurate than estimates derived from any single parameter. Because drought records inferred from ring-width data from the Canadian Prairies are relatively uncertain, adding new information from other tree-ring parameters could improve the quality of dendroclimatic reconstructions substantially.

There remains a critical need to develop more long chronologies on the Canadian prairies, either from old living trees (most promising in the eastern Rockies) or by extending living-tree records with logs recovered from historical buildings or geological settings. The current network of tree-ring sites is adequate to describe broad, regional patterns in ring width during the last 100–500 yr (varying by region), but there are not enough long chronologies to describe large-scale variability in any region prior to circa 1500 A.D. In regions like northern Saskatchewan or northwestern Ontario, the limit of tree-ring records is much more recent, with few to no trees older than 200 yr. Even with the relative abundance of old-growth trees in the foothills of the

Rocky Mountains, estimates of drought variability prior to the sixteenth century are derived from a much smaller set of tree-ring records and should be viewed with a degree of extra caution. This issue becomes only more important as we attempt to go further back in time, and as a result, it is not yet possible to use tree-ring records to adequately resolve the impacts of the ''Medieval Climate Anomaly'' (roughly 900–1300 A.D.) evident at many sites in the western United States (Cook et al. 2004b; Meko et al. 2007) and on the Canadian Prairies.

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APPENDIX A

Ring-Width Records from the Canadian Prairies

TABLE A1. Ring-width records from the Canadian Prairies used in this study. Tree species codes may be found online (http://web.utk.edu/~grissino/species.htm). Here, NA indicates information not available.

Site name	First yr	Last yr	Species*	Lat (°N)	Lon (°W)	Elev (m)	Principal investigator
Pyramid Lake	1630	1996	PSME	52.93	118.08	1200	Watson
Lake Annette	1796	1996	PSME	52.93	117.97	1150	Watson
Prairie de la Vache	1768	1996	PSME	52.80	117.97	1150	Watson
Maligne Canyon	1769	1996	PSME	52.95	117.95	1200	Watson
Whirlpool Point	730	1996	PIFL	52.00	116.27	1367	MacDonald
Powerhouse	1306	1996	PSME	51.20	115.52	1430	Watson
Swan Hills	1733	2004	PIBN	54.45	115.37	NA	Sauchyn
Pekisko Creek	1563	2004	PIFL	50.24	115.24	1515	Axelson
Stoney Indian Park	1600	2002	PSME	51.08	114.59	NA	Beriault
Towers Ridge	1599	1992	PIFL	51.10	114.40	1250	MacDonald
Wildcat Hills	1353	2004	PSME	51.15	114.40	1351	Sauchyn
Emerald Lake	1450	2004	PIFL	49.36	114.36	1384	Sauchyn
Boundary Mountain	1499	2002	PSME	48.98	114.25	1710	Pederson
Numa Ridge Falls	1645	2001	PSME	48.85	114.20	1695	Pederson
Crowsnest Pass	1466	1992	PIFL	49.35	114.13	1250	MacDonald
Little Bob Creek	1493	2004	PSME	49.56	114.13	1602	Sauchyn
Beaver Dam Creek	1482	2004	PSME	49.55	114.12	1661	Sauchyn
Lundbreck Falls	1467	1992	PIFL	49.35	114.12	1200	MacDonald
Burto Creek	1442	2004	PSME	50.01	114.11	1536	Sauchyn
Marna Lake	1627	2004	PSME	49.24	114.06	1427	Sauchyn
Dry Coulee	1734	2002	PSME	49.58	114.05	1706	Sauchyn
West Sharpies Creek	1525	2004	PSME	49.53	114.03	1575	Sauchyn
Cabin Creek	1373	2004	PSME	49.42	114.00	1395	Sauchyn
Bear Mountain Point	1455	2003	PSME	48.92	113.75	1672	Pederson
Doody Mountain	1660	2001	PSME	48.38	113.62	1890	Pederson
Going-To-Sun	1337	2002	PSME	48.70	113.52	1860	Pederson
Park Creek	1529	2003	PSME	48.35	113.50	1800	Pederson
Spot Mountain West	1663	2002	PSME	48.52	113.37	1950	Pederson
Two-Medicine Lake	1564	2001	PSME	48.48	113.37	1636	Pederson
Scenic Point	1115	2000	PIFL	48.48	113.32	2040	Pederson
Teton River Valley	783	2000	PIFL	47.92	112.73	1678	Pederson
Teton River Valley	1509	2001	PSME	47.92	112.73	1678	Pederson
Sweetgrass Hills	1446	1997	PSME	48.50	111.30	1800	Sauchyn
Sweetgrass Hills	1654	1996	PICO	48.50	111.30	1800	Sauchyn

TABLE A1. (*Continued*)

Site name	First yr	Last yr	Species*	Lat (°N)	Lon (°W)	Elev (m)	Principal investigator
Cypress Hills	1708	2001	PICO	49.40	110.00	1000	Sauchyn
Bears Paw Mountains	1558	2002	PIPO	48.15	109.30	1500	Sauchyn
Bears Paw Mountains	1581	2002	PSME	48.15	109.30	1500	Sauchyn
Maiden's Peak	1501	2003	PSME	47.11	109.13	1666	Sauchyn
Ithingo Lake	1875	2002	PIBN	56.49	107.35	500	Beriault
Fleming Island	1767	2002	PIBN	57.33	106.53	510	Beriault
Kinapik Island	1840	2001	PCGL	55.42	106.26	390	Beriault
Boundary Bog	1682	1997	LALA	53.57	106.20	611	MacDonald
Boundary Bog	1671	1997	PCMA	53.57	106.20	611	MacDonald
Heart Lakes	1769	2004	PCGL	54.00	106.12	530	Sauchyn
MacIntyre Lake	1854	2002	PIBN	57.25	106.08	500	Beriault
McGugan Island	1833	2002	PIBN	57.04	105.30	540	Beriault
Otter Rapids	1879	2001	PCGL	55.38	104.44	360	Beriault
Fraser Bay	1850	2001	PCSP	55.33	104.41	355	Beriault
Patterson Peninsula	1822	2001	PCGL	55.13	104.32	370	Beriault
Bolen Lake	1819	2002	PIBN	57.51	103.50	426	Beriault
Bolen Lake	1852	2002	PCGL	57.52	103.48	425	Beriault
Stockhouse Bay	1835	2001	PCMA	56.39	103.12	360	Beriault
Sanford Island	1878	2002	PIBN	56.30	102.58	410	Beriault
Doupe Bay	1839	2001	PCGL	54.56	102.47	315	Beriault
The Pas	1713	1994	THOC	53.83	101.24	263	Nielsen
Duck Mountain	1785	2001	BEPA	51.60	101.00	NA	Tardif
Duck Mountain	1676	2002	LALA	51.60	101.00	NA	Tardif
Duck Mountain	1717	2001	PIBN	51.60	101.00	NA	Tardif
Duck Mountain	1776	2001	PCGL	51.60	101.00	NA	Tardif
Duck Mountain	1808	2001	PPBA	51.60	101.00	NA	Tardif
Duck Mountain	1806	2001	PPTR	51.60	101.00	NA	Tardif
Masonic Island	1676	1990	QUMA	48.98	100.35	201	Meko
Easterville	1597	1988	THOC	52.92	99.18	280	Nielsen
Cedar Lake	1713	1999	THOC	53.00	99.16	NA	Tardif
Icelandic State Park	1830	1992	QUMA	48.93	97.67	297	Meko
St. Jean Baptiste	1883	1997	QUMA	49.17	97.20	235	St. George
Horseshoe Lake	1907	1999	QUMA	49.20	97.19	230	St. George
Marais River	1850	1998	QUMA	49.04	97.19	235	St. George
Bruce Park	1855	1999	QUMA	49.52	97.13	230	St. George
Parker Farm	1877	1998	QUMA	49.32	97.13	230	St. George
Fort Dufferin	1866	1999	QUMA	49.02	97.12	235	St. George
Remus Farm	1875	1998	QUMA	49.04	97.12	235	St. George
Ste. Agathe	1856	1998	QUMA	49.33	97.12	230	St. George
LaBarriere Park	1892	1998	QUMA	49.43	97.10	230	St. George
Winnipeg composite	1286	1999	QUMA	49.20	97.10	230	St. George
Munsen Park	1860	1999	QUMA	49.52	97.10	230	St. George
St. Norbert	1855	1998	QUMA	49.45	97.09	230	St. George
St. Vital Park	1830	1998	QUMA	49.45	97.08	230	St. George
Shay Farm	1907	1999	QUMA	49.39	97.07	230	St. George
Kildonan Park	1720	1999	QUMA	49.56	97.06	230	St. George
Hyland Park	1823	1999	QUMA	49.59	97.03	230	St. George
Gunisao Lake	1819	1988	PCMA	53.30	96.23	860	Schweingruber
Gunisao Lake	1896	1988	PIBN	53.30	96.23	860	Schweingruber
Bruno Lake	1822	1988	PCGL	51.62	95.83	285	Schweingruber
Mud River	1715	1983	QUMA	48.32	95.70	354	Stockton
Moose Lake	1899	2004	PIRE	49.20	95.35	362	St. George
Moose Lake	1897	2004	PIST	49.20	95.35	362	St. George
Middlebro	1802	2003	THOC	49.27	95.23	NA	Tardif
Granite Lake	1775	2004	PIRE	49.69	94.86	395	St. George
Longbow Lake	1830	2001	PIRE	49.72	94.28	339	Girardin
Longbow Lake	1789	2002	PIST	49.72	94.28	339	Girardin

TABLE A1. (*Continued*)

Site name	First yr	Last yr	Species*	Lat (°N)	Lon (°W)	Elev (m)	Principal investigator
Turtle Lake	1854	2004	PIRE	49.18	94.15	305	St. George
Turtle Lake	1862	2004	PIST	49.18	94.15	305	St. George
Kenora	1792	2001	PIRE	49.92	94.12	385	Girardin
Sioux Narrows	1772	2001	PIRE	49.42	94.05	331	Girardin
Ball Lake	1784	2004	PIST	50.32	94.00	319	St. George
Caliper Lake	1836	2004	PIRE	49.07	93.90	339	St. George/Girardin
Hillock Lake	1875	2003	PIRE	49.69	93.88	413	St. George
Maynard Lake	1801	2004	PIST	50.38	93.88	321	St. George
Red Lake	1818	2001	PIRE	51.08	93.82	354	Girardin
Sheila Falls	1853	2003	THOC	49.70	93.79	401	St. George
Expulsion Bluff	1885	2003	PIST	49.67	93.77	430	St. George
Gordon Lake	1759	2004	PIRE	49.89	93.75	396	St. George
Teggau Lake	1750	2003	PIRE	49.68	93.67	392	St. George
Clay Lake	1776	2004	PIRE	50.06	93.51	376	St. George
Lake Packwash	1852	2001	PIBN	50.77	93.43	359	Girardin
Lake Packwash	1744	2002	PIRE	50.77	93.43	359	Girardin
Snail Lake	1847	2002	PIBN	50.87	93.38	408	Girardin
Camping Lake	1827	2002	PIST	50.58	93.37	352	Girardin
Eagle Lake	1808	2001	PIRE	49.77	93.33	374	Girardin
Eagle Lake	1712	2002	PIST	49.77	93.33	374	Girardin
Highway 105	1815	2001	PIBN	50.45	93.12	377	Girardin
Onaway Lodge	1807	2004	PIRE	50.43	93.10	396	St. George
Lac Seul South	1837	2001	PIRE	50.27	92.28	361	Girardin
Lac Seul South	1762	2002	THOC	50.27	92.28	361	Girardin
Stormy Lake	1791	2001	PIRE	49.35	92.23	413	Girardin
Turtle River	1810	2001	PIST	49.25	92.22	427	Girardin
Ed Shave Lake	1700	1982	PIRE	48.08	91.97	430	Stockton
Sioux Lookout	1766	2002	PIRE	50.07	91.92	369	Girardin
Sioux Lookout	1784	2002	PIST	50.07	91.92	369	Girardin
Perch Lake	1897	2004	PIST	48.72	91.86	631	St. George
Volcano Bay	1876	2003	PIST	48.93	91.81	450	St. George
Eye Lake Ridge	1817	2003	PIST	48.89	91.70	440	St. George
Sandbar Lake	1828	2000	PIRE	49.45	91.55	431	Girardin
Sandbar Lake	1733	2002	PIST	49.45	91.55	431	Girardin
High Stone Lake	1813	1988	PCGL	50.40	91.45	398	Schweingruber
Durie Lake	1846	2003	PIST	48.97	91.26	355	St. George
Sowden Lake	1767	2004	PIST	49.53	91.21	450	St. George
‘‘The Pines’’ at Quetico	1768	2004	PIRE	48.65	91.21	411	St. George
Sowden Lake	1640	2001	PIRE	49.53	91.17	406	Girardin
Sowden Lake	1816	2002	PIST	49.53	91.17	406	Girardin
Eva Lake	1796	2003	PIST	48.71	91.17	424	St. George
Brim Lake	1797	2003	PIST	49.12	91.13	493	St. George
French Lake Portage	1878	2003	THOC	48.67	91.10	465	St. George
Windigostiwan Lake	1791	2004	PIST	48.66	91.09	450	St. George
Seagull Lake	1625	1971	PIRE	48.12	90.92	435	Fritts
Saganaga Lake	1620	1988	PIRE	48.22	90.90	435	Fritts/Graumlich
Greenwood Lake	1768	2004	PIST	48.39	90.75	503	St. George

* Codes describe the following tree species: *Betula papyrifera* Marsh. (BEPA), *Larix laricina* (Du Roi) K. Koch (LALA), *Picea glauca* (Moench) Voss (PCGL), *Picea mariana* (Mill.) (PCMA), *Picea* A. Dietr. (PCSP), *Pinus banksiana* Lamb. (PIBN), *Pinus contorta* Dougl. ex Loud. (PICO), *Pinus flexilis* James (PIFL), *Pinus ponderosa* Dougl. ex Laws. (PIPO), *Pinus resinosa* Ait. (PIRE), *Pinus strobus* L. (PIST), *Populus balsamifera* L. (PPBA), *Populus tremuloides* Michx. (PPTR), *Pseudotsuga menziesii* (Mirb.) Franco (PSME), *Quercus macrocarpa* Michx. (QUMA), and *Thuja occidentalis* L. (THOC).

APPENDIX B

Ring-Width Chronology Statistics

TABLE B1. Signal strength results for prairie ring-width standard chronologies, as calculated after Wigley et al. (1984). The expressed population signal (EPS) measures the ability of each record to represent the ideal population signal, and the between-tree correlation (R_bar) is the mean correlation between all ring-width records within a site. SSS > 0.85 is the earliest year that the chronology is able to estimate at least 85% of its original signal, derived from all trees within the stand. The median series length provides the median number of annual rings contained by the tree-ring samples from an individual site.

Site name	Species	EPS	R_bar	Cores	Trees	First yr	Last yr	SSS > 0.85	Median series length (yr)
Pyramid Lake	PSME	0.99	0.70	43	31	1630	1996	1653	226
Lake Annette	PSME	0.94	0.64	16	9	1796	1996	1819	168
Prairie de la Vache	PSME	0.98	0.72	29	17	1768	1996	1781	188
Maligne Canyon	PSME	0.94	0.57	16	11	1769	1996	1824	138
Whirlpool Point	PIFL	0.99	0.68	94	49	730	1996	822	390
Powerhouse	PSME	0.98	0.62	49	25	1306	1996	1473	292
Swan Hills	PIBN	0.90	0.44	21	11	1733	2004	1744	258
Pekisko Creek	PIFL	0.94	0.45	36	19	1563	2004	1672	285
Stoney Indian Park	PSME	0.97	0.69	22	13	1600	2002	1703	270
Towers Ridge	PIFL	0.98	0.51	76	40	1599	1992	1693	132
Wildcat Hills	PSME	0.98	0.74	32	19	1353	2004	1354	337
Emerald Lake	PIFL	0.93	0.40	36	19	1450	2004	1601	312
Boundry Mountain	PSME	0.97	0.49	58	33	1499	2002	1528	353
Numa Ridge Falls	PSME	0.95	0.53	34	18	1645	2001	1676	214
Crowsnest Pass	PIFL	0.98	0.45	86	49	1466	1992	1531	157
Little Bob Creek	PSME	0.98	0.64	47	23	1493	2004	1598	310
Beaver Dam Creek	PSME	0.97	0.59	42	22	1482	2004	1583	346
Lundbreck Falls	PIFL	0.97	0.49	65	38	1467	1992	1674	184
Burto Creek	PSME	0.93	0.51	20	12	1442	2004	1669	287
Marna Lake	PSME	0.94	0.48	34	17	1627	2004	1722	257
Dry Coulee	PSME	0.95	0.49	33	18	1734	2002	1809	170
West Sharpies Creek	PSME	0.98	0.61	63	31	1525	2004	1585	360
Cabin Creek	PSME	0.98	0.68	44	23	1373	2004	1409	410
Bear Mountain Point	PSME	0.97	0.39	86	54	1455	2003	1579	270
Doody Mountain	PSME	0.95	0.48	35	20	1660	2001	1703	231
Going-To-Sun	PSME	0.91	0.46	20	12	1337	2002	1611	333
Park Creek	PSME	0.95	0.50	35	20	1529	2003	1616	274
Spot Mountain West	PSME	0.97	0.43	58	38	1663	2002	1366	316
Two-Medicine Lake	PSME	0.96	0.43	47	33	1564	2001	1665	212
Scenic Point	PIFL	0.94	0.37	47	28	1115	2000	1242	317
Teton River Valley	PIFL	0.94	0.34	43	29	783	2000	1161	273
Teton River Valley	PSME	0.94	0.38	41	25	1509	2001	1578	283
Sweetgrass Hills	PSME	0.95	0.40	47	28	1446	1997	1690	271
Sweetgrass Hills	PICO	0.94	0.37	42	27	1654	1996	1727	258
Cypress Hills	PICO	0.93	0.41	37	21	1708	2001	1885	101
Bears Paw Mountains	PIPO	0.96	0.47	44	26	1558	2002	1766	161
Bears Paw Mountains	PSME	0.98	0.55	62	35	1581	2002	1733	200
Maiden's Peak	PSME	0.89	0.43	21	11	1501	2003	1680	300
Ithingo Lake	PIBN	0.86	0.31	20	14	1875	2002	1885	118
Fleming Island	PIBN	0.88	0.31	30	17	1767	2002	1884	119
Kinapik Island	PCGL	0.97	0.57	52	27	1840	2001	1847	135
Boundary Bog	LALA	0.97	0.55	41	27	1682	1997	1686	179
Boundary Bog	PCMA	0.90	0.38	45	14	1671	1997	1831	135
Heart Lakes	PCGL	0.93	0.42	39	20	1769	2004	1809	175
MacIntyre Lake	PIBN	0.87	0.31	23	15	1854	2002	1878	125
McGugan Island	PIBN	0.88	0.33	26	15	1833	2002	1848	139

TABLE B1. (*Continued*)

Site name	Species	EPS	R_bar	Cores	Trees	First yr	Last yr	SSS > 0.85	Median series length (yr)
Otter Rapids	PCGL	0.96	0.50	33	21	1879	2001	1884	105
Fraser Bay	PCSP	0.95	0.45	38	21	1850	2001	1868	99
Patterson Peninsula	PCGL	0.96	0.52	43	22	1822	2001	1840	133
Bolen Lake	PIBN	0.88	0.40	25	11	1819	2002	1856	134
Bolen Lake	PCGL	0.94	0.53	26	14	1852	2002	1891	99
Stockhouse Bay	PCMA	0.89	0.31	33	18	1835	2001	1862	131
Sanford Island	PIBN	0.95	0.49	30	19	1878	2002	1882	118
Doupe Bay	PCGL	0.94	0.43	34	22	1839	2001	1883	109
The Pas	THOC	0.93	0.45	58	16	1713	1994	1841	116
Duck Mountain	BEPA	0.95	0.27	86	49	1785	2001	1882	100
Duck Mountain	LALA	0.91	0.31	33	23	1676	2002	1743	106
Duck Mountain	PIBN	0.98	0.27	242	133	1717	2001	1892	107
Duck Mountain	PCGL	0.93	0.38	40	20	1776	2001	1852	115
Duck Mountain	PPBA	0.91	0.33	31	21	1808	2001	1892	104
Duck Mountain	PPTR	0.98	0.29	175	124	1806	2001	1891	103
Masonic Island	QUMA	0.87	0.42	16	9	1676	1990	1821	158
Easterville	THOC	0.93	0.49	39	14	1597	1988	1719	132
Cedar Lake	THOC	0.93	0.29	54	31	1713	1999	1825	138
Icelandic State Park	QUMA	0.91	0.40	27	15	1830	1992	1880	109
St. Jean Baptiste	QUMA	0.92	0.53	10	10	1883	1997	1897	101
Horseshoe Lake	QUMA	0.90	0.54	8	8	1907	1999	1912	89
Marais River	QUMA	0.93	0.49	15	13	1850	1998	1887	109
Bruce Park	QUMA	0.95	0.55	15	15	1855	1999	1881	101
Parker Farm	QUMA	0.97	0.59	33	22	1877	1998	1880	119
Fort Dufferin	QUMA	0.94	0.59	20	12	1866	1999	1881	112
Remus Farm	QUMA	0.95	0.64	10	10	1875	1998	1880	117
Ste. Agathe	QUMA	0.94	0.58	12	11	1856	1998	1869	119
LaBarriere Park	QUMA	0.93	0.58	9	9	1892	1998	1897	101
Winnipeg composite	QUMA	0.98	0.30	187	96	1286	1999	1517	133
Munsen Park	QUMA	0.91	0.51	9	9	1860	1999	1869	128
St. Norbert	QUMA	0.91	0.52	10	10	1855	1998	1864	134
St. Vital Park	QUMA	0.93	0.45	24	16	1830	1998	1855	127
Shay Farm	QUMA	0.94	0.62	10	10	1907	1999	1909	92
Kildonan Park	QUMA	0.97	0.49	43	37	1720	1999	1854	131
Hyland Park	QUMA	0.97	0.56	42	25	1823	1999	1869	110
Gunisao Lake	PCMA	0.76	0.21	19	12	1819	1988	1902	90
Gunisao Lake	PIBN	0.86	0.44	13	8	1896	1988	1900	89
Bruno Lake	PCGL	0.91	0.45	22	12	1822	1988	1848	140
Mud River	QUMA	0.92	0.54	20	10	1715	1983	1763	143
Moose Lake	PIRE	0.95	0.58	28	14	1899	2004	1899	104
Moose Lake	PIST	0.96	0.71	20	10	1897	2004	1903	99
Middlebro	THOC	0.88	0.43	19	10	1802	2003	1868	123
Granite Lake	PIRE	0.96	0.50	38	22	1775	2004	1799	154
Longbow Lake	PIRE	0.96	0.54	43	21	1830	2001	1838	159
Longbow Lake	PIST	0.97	0.61	36	18	1789	2002	1844	130
Turtle Lake	PIRE	0.95	0.52	33	17	1854	2004	1870	121
Turtle Lake	PIST	0.96	0.58	29	16	1862	2004	1877	112
Kenora	PIRE	0.93	0.39	37	21	1792	2001	1829	129
Sioux Narrows	PIRE	0.95	0.56	40	16	1772	2001	1817	142
Ball Lake	PIST	0.96	0.59	35	18	1784	2004	1807	172
Caliper Lake	PIRE	0.96	0.53	49	24	1836	2004	1846	147
Hillock Lake	PIRE	0.88	0.45	17	9	1875	2003	1883	120
Maynard Lake	PIST	0.96	0.57	33	17	1801	2004	1821	167
Red Lake	PIRE	0.94	0.43	40	20	1818	2001	1826	163
Sheila Falls	THOC	0.91	0.35	34	19	1853	2003	1883	115
Expulsion Bluff	PIST	0.76	0.45	6	4	1885	2003	1894	102
Gordon Lake	PIRE	0.87	0.29	34	17	1759	2004	1843	157

Table B1. (*Continued*)

Site name	Species	EPS	R_bar	Cores	Trees	First yr	Last yr	SSS > 0.85	Median series length (yr)
Teggau Lake	PIRE	0.87	0.34	25	13	1750	2003	1896	105
Clay Lake	PIRE	0.97	0.55	46	23	1776	2004	1783	216
Lake Packwash	PIBN	0.61	0.24	9	5	1852	2001	1913	94
Lake Packwash	PIRE	0.93	0.39	37	20	1744	2002	1828	169
Snail Lake	PIBN	0.77	0.27	15	9	1847	2002	1898	103
Camping Lake	PIST	0.91	0.42	26	14	1827	2002	1851	131
Eagle Lake	PIRE	0.94	0.41	37	21	1808	2001	1826	158
Eagle Lake	PIST	0.93	0.47	28	15	1712	2002	1803	154
Highway 105	PIBN	0.92	0.37	34	20	1815	2001	1819	155
Onaway Lodge	PIRE	0.91	0.40	29	15	1807	2004	1821	180
Lac Seul South	PIRE	0.88	0.29	39	19	1837	2001	1861	133
Lac Seul South	THOC	0.94	0.48	33	16	1762	2002	1875	122
Stormy Lake	PIRE	0.81	0.32	22	9	1791	2001	1815	166
Turtle River	PIST	0.89	0.41	21	12	1810	2001	1843	122
Ed Shave Lake	PIRE	0.95	0.51	37	18	1700	1982	1797	150
Sioux Lookout	PIRE	0.77	0.29	15	8	1766	2002	1814	163
Sioux Lookout	PIST	0.90	0.38	29	15	1784	2002	1848	125
Perch Lake	PIST	0.90	0.41	22	13	1897	2004	1909	91
Volcano Bay	PIST	0.93	0.61	18	9	1876	2003	1881	112
Eye Lake Ridge	PIST	0.95	0.55	30	16	1817	2003	1824	147
Sandbar Lake (PIRE)	PIRE	0.93	0.46	31	16	1828	2000	1900	100
Sandbar Lake (PIST)	PIST	0.91	0.35	35	19	1733	2002	1897	105
High Stone Lake	PCGL	0.91	0.49	22	11	1813	1988	1828	152
Durie Lake	PIST	0.85	0.41	14	8	1846	2003	1887	119
Sowden Lake	PIST	0.97	0.61	36	18	1767	2004	1783	172
"The Pines" at Quetico"	PIRE	0.95	0.32	73	37	1768	2004	1777	196
Sowden Lake	PIRE	0.93	0.43	36	18	1640	2001	1748	234
Sowden Lake	PIST	0.93	0.44	30	17	1816	2002	1849	123
Eva Lake	PIST	0.88	0.35	22	13	1796	2003	1861	131
Brim Lake	PIST	0.90	0.46	20	10	1797	2003	1846	150
French Lake Portage	THOC	0.85	0.39	16	9	1878	2003	1901	104
Windigostiwan Lake	PIST	0.95	0.50	31	17	1791	2004	1823	130
Seagull Lake	PIRE	0.94	0.51	29	15	1625	1971	1684	262
Saganaga Lake	PIRE	0.98	0.47	139	66	1620	1988	1675	205
Greenwood Lake	PIST	0.98	0.50	85	44	1768	2004	1778	175

APPENDIX C

Chronology Development and Calculating Regional Tree-Ring Series

a. Chronology development

Age- or size-related trends in ring-width data were removed by dividing each series by a spline with a 50% response wavelength equal to 70% of the length of each ring-width series (Cook et al. 1990). Because tests conducted using a much stiffer spline (a response wavelength equal to 200% of the series length) produced very similar results, we concluded that our analyses were largely insensitive to the choice of standardization approach. The same spline parameters were also used to remove any trend in variance. Detrended ring-width series were then combined to create the site chronology, with variance stabilization (Osborn et al. 1997) applied to adjust for changes in the number of trees over time.

The strength of the population signal in each chronology was assessed using the mean between-tree correlation and the EPS statistic (Wigley et al. 1984; appendix B). Nearly all sites have EPS values above 0.85 (used commonly as a minimum threshold for chronology quality). Although most sites with very high between-tree correlations (0.6 and above) are located in the eastern Rockies, there are no other apparent differences in the quality of the within-stand signal retained by ring-width chronologies in each of the five regions. Chronologies become increasingly noisy back in time, as fewer and fewer trees are available to contribute to the estimate of the population mean. Eventually, the chronology is derived from so few trees that the signal becomes obscured by an unacceptable amount of noise. The subsample signal strength (SSS;

Wigley et al. 1984) is a measure of the chronology's ability to retain its original signal (estimated from all trees within the stand) back through time. We truncated each chronology at the point where the SSS fell below 0.85 and excluded years prior to this cutoff from the final chronology.

b. Regional ring-width signals

The application of the EOF technique used correlation matrices derived from the regional ring-width networks, with no rotation applied (using covariance matrices or varimax rotation produced similar leading EOFs). Higher-order EOFs either could not be resolved from random white noise using the rule N significance test (Overland and Preisendorfer 1982) or exhibited the same seasonal moisture sensitivity as the leading EOF.

EOF analysis was conducted on ring-width chronologies from each of the five regions separately for the period 1900–2004. In some cases, the principal component time series (PC) associated with EOF1 is almost identical to a simple average of all chronologies in the region. Over the period 1900–2004, the first eigenvectors describe between 30% and 60% of the regional networks' total variance (Fig. 2).

This initial analysis suggested that robust spatiotemporal patterns could be resolved from each of the five regional tree-ring networks. However, as with individual chronologies, the pool of available records across each region becomes smaller back in time as shorter chronologies become unavailable. Therefore, it is necessary to test whether a progressively shrinking network of chronologies can still provide an accurate estimate of the patterns described by the full network. We conducted a series of nested EOF analyses using a series of overlapping time intervals, each with the same end year but with different beginning years. In each run, chronologies were allowed to enter as inputs if they spanned more than 85% of the interval. Chronologies that did not span the entire interval were padded by replacing missing values with the global mean (Kim and North 1993). The quality of the signal recovered from the reduced network was assessed by comparing the PCs associated with the leading EOFs against those derived from the full network. If the reduced network produced PCs that were highly correlated ($r > 0.9$) with the PCs from the full network, we concluded that the reduced network was adequate to describe the behavior of that pattern back in time. The analysis was terminated once the PCs from the reduced network began to diverge from the original PCs. Essentially, this approach seeks to maximize the length of the regional PCs while retaining enough sites to define the spatiotemporal pattern accurately.

For the eastern Rockies, the leading pattern (EOF1) defined from the full network of 38 chronologies can be resolved using only the 14 longest chronologies. Because the pattern begins to degrade if fewer chronologies are used, we conclude that EOF1 can be resolved adequately back to 1528. Only seven chronologies are required to resolve EOF1 in northern Saskatchewan back to 1839. The leading eigenvector in the northwestern Ontario network can be described using only 12 chronologies and is stable back to 1783. Unlike the other regions, the first PC from central Manitoba changes radically as chronologies become unavailable back in time; extending the period of analysis by only 25 yr (beginning in 1875 instead of 1900) produces a PC that is only weakly correlated ($r = 0.39$) with the leading PC derived from the full network. This behavior is likely caused by having too few chronologies (10) in this region to define the initial pattern properly, weak correlations between the chronologies, and by having six chronologies (from different tree species) at the same geographic location.

The nested EOF approach is not appropriate for the set of chronologies from southern Manitoba. This set is made up of several short chronologies (most are less than 150 yr long), and a single long chronology (''Winnipeg composite'') developed from trees taken from historical buildings and alluvial deposits. Although this chronology extends up to 1999, the twentieth-century portion of its record is derived from very few trees. Because this chronology is weakest in the most recent portion of its record, it is not reasonable to judge the quality of its signal based on its ability to mirror regional ring-width variability during the twentieth century. As an alternative, we combined all ring-width data for southern Manitoba and constructed a single regional tree-ring record [this approach is similar to the strategy used by St. George and Nielsen (2002)]. Applying the EPS criterion to the regional series suggests that it remains a reasonable approximation of the unknown population signal back to 1523 A.D.

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