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Frost-ring chronologies as dendroclimatic proxies of boreal environments

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[1] Frost rings are formed in tree stems when growing-season frosts affect immature wood cells, producing collapsed cells within annual tree rings. Open boreal forests are most susceptible to record growing-season frost because they lack the greenhouse effect commonly observed in closed forests. Here we present a novel method to construct regional frost-ring chronologies in lichen-black spruce woodlands of the boreal forest zone. Because the ability of trees to form frost rings depends on several factors (including bark thickness and ring width), we used two models to produce a Frost Composite Index based on a frost susceptibility window of cambial age <30 years. The frost-ring chronology showed alternating periods of high and low frost activity that were highly consistent within and among sites. Reconstruction of growing-season frost activity may be used as dendroclimatic proxies of climate variability and may give insights into future risks of frost damage in a warming climate. **Citation:** Payette, S., A. Delwaide, and M. Simard (2010), Frost-ring chronologies as dendroclimatic proxies of boreal environments, *Geophys. Res. Lett.*, *37*, L02711, doi:10.1029/2009GL041849.

1. Introduction

[2] Outside the Tropics, temperate, boreal and arctic biomes are within the realm of seasonal frost. Plant species distribution across the Globe is largely dependent on seasonal frost influence [*Woodward*, 1987]. Most plants in cold-based biomes must develop winter hardness in order to survive winter conditions. Winter hardness in conifer species of the circumboreal forest includes morphological and physiological adaptations (bud scales, dormancy, extracellular equilibrium freezing, etc.) to extreme cold and dry winter conditions [*Havranek and Tranquillini*, 1995]. These adaptations are generally sufficient to resist the predictable cold temperatures in winter. The situation differs markedly during the growing season when unpredictable frosts are occurring. Whereas alpine plants in the Tropics have developed sophisticated structural and physiological devices to resist daily frosts throughout the year-round growing season [*Rundel et al.*, 1994], all boreal and arctic species are not adapted to frost occurring during the growing season. As a consequence, all kinds of summer frost damage are imposed to plant tissues depending on frost severity, phenological stages and species tolerance. Besides leaf and bud destruction associated with summer frost [*Bigras and Hébert*, 1996], xylem damage in the form of a frost ring is one of the most striking and common features recorded in woody species [*Glerum and Farrar*, 1966; *Glock*, 1951]. Frost rings appear as one or several rows of collapsed cells with poorly developed cell walls caused by severe growing-season frost events that disrupt anatomical development of the xylem (auxiliary material Figure S1).[3] The specific anatomical characteristics of frost rings have been described [*Glerum and Farrar*, 1966] and allow their discrimination from other tree-ring anomalies such as false rings [*Wimmer et al.,* 2000] and light rings [*Filion et al.*, 1986; *Delwaide et al.*, 1991]. The most remarkable features of a frost ring are the deformation of tracheids, the curvature of rays and the subsequent development of callus tissue [*Schweingruber*, 2007].

[3] Frost rings are among a family of diagnostic rings used as a dendroecological tool to reconstruct past environmental and climatic changes in climate-sensitive forest ecosystems [*Dy and Payette*, 2007; *Hantemirov et al.*, 2004; *LaMarche and Hirschboeck*, 1984]. Frost rings in the conifer black spruce (*Picea mariana* [Mill.] B.S.P.) are formed when nocturnal temperatures are below 0°C during 6 hours and reach −6°C [*Dy and Payette*, 2007]. Frost rings in subalpine bristlecone pines (*Pinus longaeva* D. K. Bailey and *P. aristata* Engel.) in western USA were reported to correspond with major volcanic eruptions over the past several hundred years [*LaMarche and Hirschboeck*, 1984]. The climatic effects of volcanic eruptions due to stratospheric aerosol veils are responsible for the occurrence of frost rings in western USA, and also light rings (rings with thin−walled latewood cells) distributed across the subarctic part of the North American boreal forest [*Filion et al.*, 1986; *Delwaide et al.*, 1991] and Siberia [*Hantemirov et al.*, 2004].

[4] Besides the coincidence of several frost events with volcanic eruptions in subalpine sites of western USA, frost ring occurrences are frequent and widely distributed across the circumboreal environment in close association with daily weather conditions. The frequency of frost action varies greatly according to location, structure, and stage of development of forests [*Geiger et al.*, 2003]. Given the climatic signature of frost rings as markers of severe frost events occurring during the growing season, the construction of frost-ring chronologies may be used as proxies of climate variability in the forest environment. In this study, we present a novel method to construct frost-ring chronologies using a large dataset of black spruce trees growing in lichen woodlands of southern Québec (Canada). Such chronologies could enhance our understanding of the effect of minimum temperatures on risk of frost damage, which

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[3]Auxiliary materials are available in the HTML. doi:10.1029/2009GL041849.

could paradoxically increase under a warming climate because of earlier springs [*Hänninen*, 2006; *Rigby and Porporato*, 2008].

2. Methods

[5] The studied black spruce trees come from five different sites, all located at an average elevation of 750 meters a.s.l. and within a radius of 10 km of the Parc national des Grands-Jardins (hereafter PGJ), southern Québec (47°40′N/70°50′W). All stands were post-fire, even-aged lichen woodlands, growing on well-drained, sandy podzolic soils. Three of the stands (AN, AS, and RSA) burned in June 1991 and the last rings analyzed corresponded to the year 1990. The BO and LC stands were studied in 1997 and 2003, and the last rings analyzed were 1996 and 2002, respectively. Each sampling quadrat (1500 to 2500 m^2) was located at the center of each site, and all trees >2 cm at breast height were cross-sectioned at <30 cm from the ground, except at site RSA where 30 dominant trees were sampled. The cross-sections were dried and polished until xylem cells were visible under a binocular microscope at 40×. Annual ring widths of each sample were then measured using a Velmex micrometer (±0.002 mm) along two opposite radii and compared statistically using the program COFECHA [*Holmes*, 1983]. On each cross-section, all frost rings were recorded along two opposite radii. In addition, we noted if the position of frost-damaged cells within the tree-ring was at the beginning (first half of the earlywood), middle (second half of the earlywood), or end (latewood cells) of the ring (Figure S1).

[6] The first step in the construction of the frost-ring chronology was to identify all frost rings and calculate their annual relative frequency (%) at each site, i.e., the number of frost rings divided by the total number of rings examined for that year (Figure 1). This allowed the comparison of inter-annual patterns of frost activity within and among sites. Despite the age difference among sampled sites, there was a general agreement among the different raw chronologies (Kolmogorov-Smirnov test: D < 0.05 for all sites compared except for the youngest AS site), which allowed the second step to be completed, i.e., the construction of the frost-ring chronology proper.

[7] A major impediment to the construction of frost-ring chronologies is that the tree's ability to record a frost ring is not uniform throughout its lifetime. Tree bark plays a crucial role in the thermal protection of the cambium. As bark thickness increases with time, tree rings gradually loose their ability to record frost events, and all frost rings observed on a cross-section are in the first few cm from the pith. Ring width is also a factor that must be considered because frosts only affect tracheids that are in the differentiation process. Therefore, wide rings are more likely to include frost marks than narrow rings [*Schweingruber*, 2007].

[8] To account for the changing sensitivity with cambial age (the age of a ring relative to the stem pith) and with ring width, we used two methods that yielded two different chronologies. In the first method, we modeled sensitivity to frost as a function of cambial age by fitting a Weibull function to the empirical distribution of all frost rings within each site (Figure S2). The resulting Weibull functions represented the 'susceptibility window' of an individual tree-ring series, i.e., the probability that a ring would record frosts according to its cambial age. We then calculated the stand-level probability to record frost events at a given site by adding, for each calendar year, the susceptibility windows of all sampled trees in a site, using tree establishment dates (cambial age = 1), to place each susceptibility window in calendar time. The Weibull Index (WI) was obtained by dividing, for each calendar year, the observed number of frost rings by the stand-level probability to record frost events. The second method assumed a constant, decreasing probability of frost ring formation with time for all rings <30 years of cambial age. Use of a 30-year frost susceptibility window was based on the observation that most frost rings (97%) were formed in stems <30 years of age. The relative frequency (%) of frost rings <30 years old was calculated for each calendar year, and a linear regression was fit to the log-transformed values. The Semi-Log Index (SLI) corresponds to the residuals of the regression (Figure S3). The SLI method is a stand-level model fitting age/size distribution of trees in forest stands of different ages. The two indices were combined into a Frost Composite Index (FCI) to strengthen the overall trends of both indexed frost-ring series. Because both indices had a different scale, we divided the yearly values of each index by their respective average. The FCI represents the average of the two indices, and only values above 0 were retained for generalization. The frost-ring chronology was built from the values of the FCI.

[9] Because long weather series were not available for the study area, the Québec City station, 120 km southwest of the PGJ, was used to document low temperatures. The temperature series covered the period 1877-2002. Weather data from the Québec City station appeared representative of temperature trends in the PGJ as mean June and July temperatures recorded over a 12-year period in a lichen woodland of the park were well correlated (r = 0.87, p < 0.001 for mean monthly temperature and r = 0.85, p < 0.001 for mean monthly minimum temperature) to the weather station data. Frost-ring occurrences were compared with daily minimum temperatures of the Québec City station. For this period, a mean difference of 5.8°C (±1.02°C) was calculated between summer temperature of the weather station and that of the PGJ. We used June and July minimum temperature data in the analysis of frost-ring occurrence because most frost rings (>95%) were located in the earlywood of tree rings.

3. Results

3.1. Characteristics and Distribution of Frost-Ring Years

[10] A total of 831 stem cross-sections were sampled, and 5253 frost rings were recorded among a population of 36421 tree rings (Table 1). Nearly 60% of all frost rings occurred in the first half of the earlywood, and those recorded in the middle or at the end of the earlywood cell rows corresponded to 35% of all frost rings. Only 5% of frost events were recorded in latewood cells. The distribution of frost-ring width differed significantly from the distribution of normal ring width (KS test: D >0.05) in each site, but mean tree-ring width did not significantly differ between frost-affected and frost-free rings (P = 0.77;

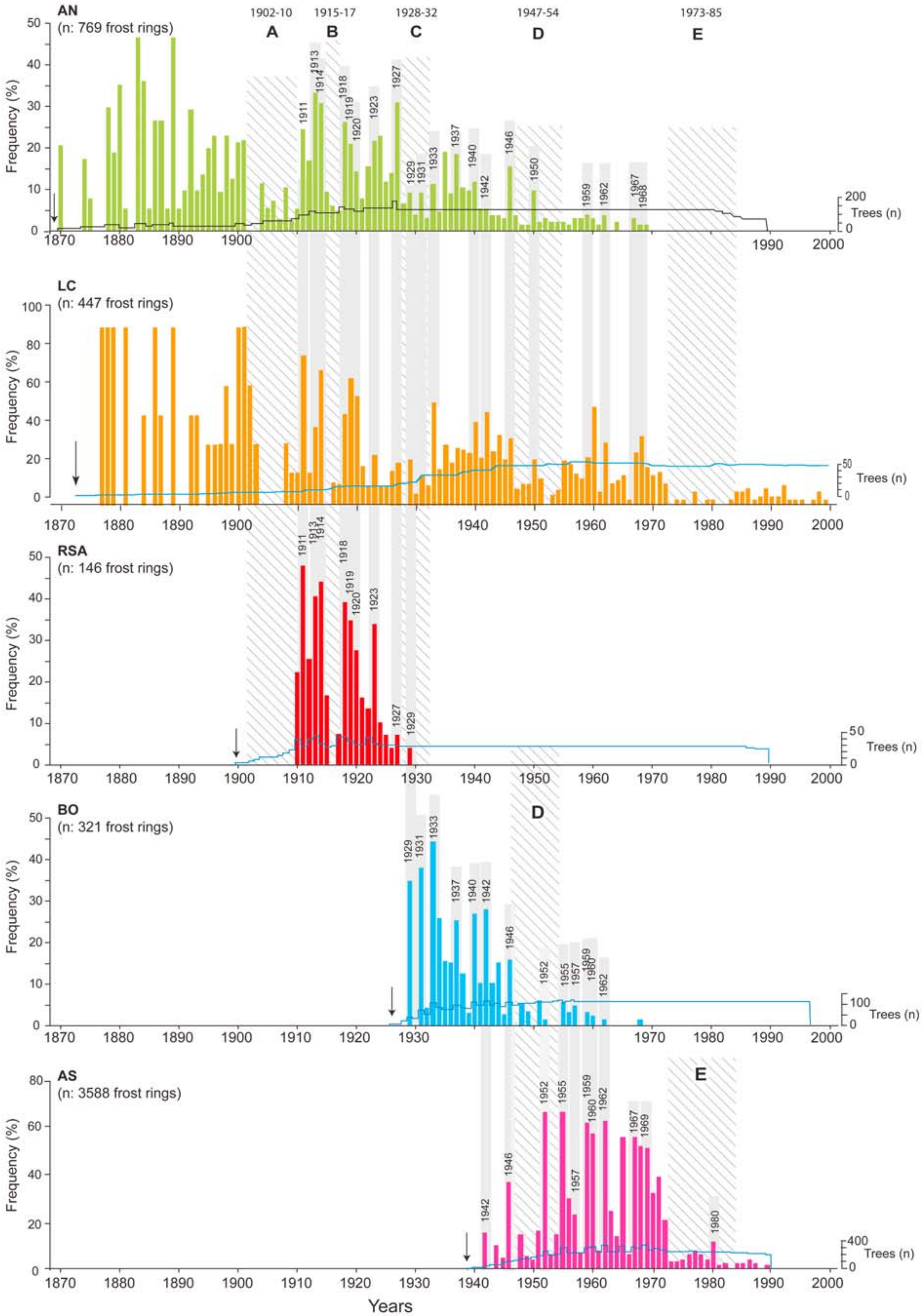

Figure 1. Annual relative frequency of frost rings at each site (bars). Arrows indicate the first ring analyzed, and curves represent sample depth. Periods of increased and reduced frost ring occurrence are highlighted by light gray bars and hatched areas (A to E), respectively.

Table 1. Stand Structure and Characteristics of Observed Frost Rings at Each Site[a]

	AN	AS	LC	RSA	BO	Total
Trees (n)	121	496	52	30	132	831
Trees (n/ha)	484	1984	333	n.m.	880	
Mean diameter of trees (cm)	15.4	6.8	n.m.	10.0	17.1	
Standard deviation (cm)	8.6	3.3	n.m.	3.9	6.0	
Dominant plant cover[b]	C, B, V, P	C, B, P, V	C, B, P, R	V, R, C, P	C, V, R, P	
Observed rings (n)	10215	12745	3676	2437	7348	36421
Frost rings (n)	769	3570	447	146	321	5253
Maximum cambial age of frost rings	53	43	47	21	19	
Position of frost damage in the ring						
Beginning	550	1926	321	109	224	3130
Middle	130	1599	63	30	54	1876
End	89	45	63	7	43	247
Mean ring width without frost[c] (mm)	0.433	1.159	n.m.	1.642	1.704	
Mean ring width with frost[c] (mm)	0.553	0.728	n.m.	1.128	1.462	
Kolmogorov-Smirnov test (D)	0.14	0.17		0.25	0.18	

[a]Here n.m. means not measured.
[b]Dominant plant cover (arranged in decreasing abundance): C, *Cladonia* sp.; B, *Betula glandulosa*; V, *Vaccinium angustifolium*; P, *Picea mariana*; and R, *Rhododendron groenlandicum*.
[c]Mean ring widths are for rings <30 years of cambial age.

mixed effect model with log-transformed ring width as the response variable, presence/absence of frost as a fixed effect, and site and its interaction with presence/absence of frost as random effects; only rings <30 years of cambial age were analyzed).

[11] The relative frequency of frost rings calculated for each woodland stand varied with stand age and year of tree establishment (Figure 1). AN and LC sites recorded frost rings over a period of 100 years, and RSA, BO and AS sites over a period not exceeding 50 years. Frost ring frequency from stand inception (arrows in Figure 1) to sampling year reflects the changing capacity of trees to record frost events as their bark thickens in sites with a short regeneration window. However, in older sites (AN, LC), continuous tree regeneration extends the frost-ring record. This effect is particularly important in stands RSA and BO where an abundant post-fire cohort of trees was followed by little or no establishment, and highlights the need to correct for this effect using the WI and SLI. Frost rings were formed almost every year in most sites, but at a frequency <5% in several cases. High-frequency frost-ring years (grey bars in Figure 1) and low-frequency frost-ring years (periods A to E in Figure 1) were common in each site and synchronous among sites. A notable reduction in frost-ring frequency over the period 1902–1910 occurred at AN and LC sites, whereas no frost ring was formed at RSA site during this period in spite of tree establishment during the early twentieth century (period A in Figure 1). The years 1915 to 1917 were also a period of minimal occurrence or absence of frost rings in the latter sites, particularly at RSA site. The reduced occurrence of frost rings between 1928 and 1932 at AN and LC sites was echoed at RSA site by the sudden interruption of the frost-ring sequence. Reduced frost activity between 1947 and 1954 was also recorded at BO and AS sites. After 1973, only a small number of frost rings at sites AN and LC was recorded, due in part to the advanced age of trees.

[12] Most frost rings were formed at a young cambial age, although maximum age of frost ring inception varied between 19 and 53 years (Table 1). At AS, LC and RSA sites, cambial-age frequency distribution was symmetric, whereas for AN and BO sites the distribution was right-skewed, with a larger number of frost occurrences in relatively young rings (Figure S2). The maximum number of frost rings was recorded 5 to 20 years after tree establishment in each site, and frost-ring frequency gradually decreased thereafter.

3.2. Frost Composite Index

[13] Both WI and SLI chronologies (Figure S4) showed similar trends of frost activity through time (R Pearson:0.62, n:133, P<0.001; Gleichläufigkeit test:0.82) that were also consistent with the raw chronologies (Figure 1). The larger variability of the indexed values prior to 1900 and after 1990 is attributable to the small number of rings examined (<50 samples). FCI included 66 frost-ring years identified out of 133 years (1870–2002) of record (Table S1 and Figure 2a).

[14] FCI was compared to minimum June and July temperatures of the Québec City weather station. Of the 66 frost rings, 30 were associated with particularly low temperatures (below the 1951–80 normals) during June and/or July (Figures 2c and 2d). Twenty-three out of 66 frost-ring years coincided with below-average minimum June temperature, and the same number was also coincident with below-average minimum July temperature (Figures 2a, 2c, and 2d). However some years of low June temperature were not associated with high incidence of frost rings. Among the years with the lowest mean June temperatures recorded, years 1881, 1890, 1897, 1902, 1912, 1958 and 2002 did not induce the formation of a frost ring. All these years were characterized by low mean June temperature (Figure 2e). Radial growth was probably delayed and may have reduced the probability of frost action on cell development. Furthermore, no significant relationship was found between frost-ring incidence and both warmer and colder mean June temperature over the last 100 years (R^2 = 0.005, P = 0.812), suggesting that inception of frost rings is more often associated with daily extreme temperatures than it is to monthly temperature averages.

4. Discussion

[15] Frost-ring ecology in boreal environments differs in many ways from that of the western USA. In open boreal

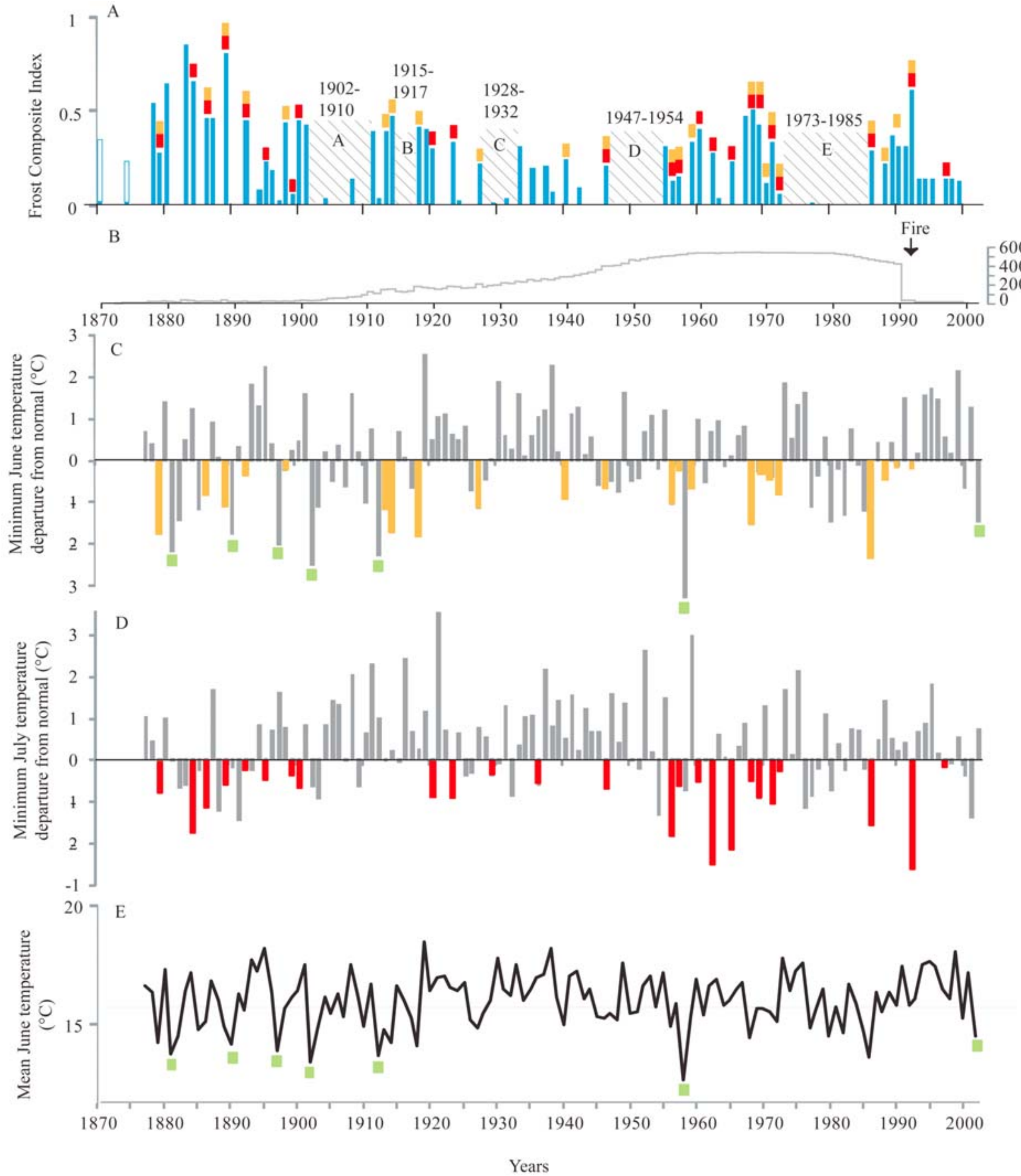

Figure 2. Relationship between the Frost Composite Index and temperature data from the Québec City weather station. (a) Frost Composite Index. Frost rings associated with below-normal minimum temperature are identified by a yellow (for June) and/or red (for July) squares. (b) Number of trees analyzed per year. (c) Minimum June temperature departure from 1877–2002 normals. Yellow bars correspond to frost ring years identified in Figure 2a. Low temperatures not associated with frost rings are identified by a green square. (d) Minimum July temperature departure from 1877–2002 normals. Red bars correspond to frost ring years identified in Figure 2a. (e) Mean June temperature. Green squares correspond to those identified in Figure 2c.

forests, frost rings occur almost every year, are produced in the earlywood part of the ring, and can only be found in the first 30 years or so of cambial age in black spruce. The small number of frost rings in the first 10 years of growth strongly suggests that bark thickness is not the only factor involved in the formation of frost rings. We speculate that the typically narrow rings produced in the first years following tree establishment (Figure S6) may have a lower propensity to record frost events because at any given time, a smaller number of cells are in the differentiation phase, the period during which tracheids are most vulnerable to frost [*Schweingruber*, 2007]. In contrast, frost rings in the American Southwest are produced at intervals of a few decades to a few hundreds years, are primarily found in the latewood of tree rings, and can be observed in >300 years-old bristlecone pines. Formation of frost rings in western USA has been linked to late-summer and early fall cold spells during years colder than average [*LaMarche and Hirschboeck*, 1984; *Brunstein,* 1996]. In contrast to these pine species which could experience a delay in cell maturation during cold summers, cessation of latewood cell production in spruce always occurs in August at the latest (unpublished dendrometer data). This explains, at least in part, why few frost rings in spruce occur in latewood cells. Frost rings appear to be less frequent during years when early summers are colder than average, possibly as a result of delayed onset of radial growth.

[16] The high frequency of growing-season frosts and short time window for individual trees to record these frosts (about 30 years) present a challenge for compiling frost-ring chronologies in boreal environments. The FCI method presented here was an attempt to address these challenges and allowed the reconstruction of frost-ring frequency in lichen woodland stands since 1870. The chronology was based on a large number of all-aged samples that allowed an adequate number of young 'recorder' trees to be present at any given year of the chronology. Almost all frost rings recorded were associated with particularly low temperature minima in June and/or July at the Québec City weather station. However, even if the average temperatures between the two areas were well correlated, some frost rings did not correspond to low temperatures, and some low temperatures did not produce frost rings. In the first case, this discrepancy may be due to the long distance (120 km) between the weather station and the sampled stands, and may be an indication of the spatial extent of some frost events in the region. In the second case, the mismatch may be explained by cooler than average early summers that delay onset of radial growth (Figure 2e). Future research should aim at identifying the conditions that lead to these situations.

[17] Frost rings are not only useful as climatic proxies but can also be used as marker rings for cross-dating problematic tree-ring series [*Bailey*, 1925]. Compared to other types of diagnostic rings, frost rings have two additional characteristics as marker rings. Frost-damaged cells occur at specific locations within the ring, depending on the timing of the frost event relative to the onset of the growing season, and multiple frost rings also can occur during a single year [*Gurskaya and Shiyatov*, 2002]. The frost-ring chronology that we developed here shows years that have a single frost event recorded at the beginning, middle or end portion of the ring, as well as years with several frost events with different combinations of damage position (Table S1). Frost-ring chronologies can be used to cross-date tree-ring series according to the temporal pattern of frost-ring years, but also on the characteristics of each ring (position and number of rows of damaged cells) that in many cases provide fingerprint-like specificity.

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