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Observed continentality in radial growth–climate relationships in a twelve site network in western Labrador, Canada

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ABSTRACT

Despite their suitability for dendroclimatological research, the boreal regions of central and western Labrador remain under-researched. In an attempt to evaluate the growth trends and climatic response of this region's trees, master chronologies have been developed for its four dominant conifer species. Balsam fir (*Abies balsamea* (L.) Mill.), white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) Britton, Sterns, Poggenb.) and eastern larch (*Larix laricina* (DuRoi) K. Koch) were sampled systematically within a 3 × 4 grid of twelve sites at the intersection of 62°W, 64°W and 66°W longitude, and latitudes 52°N, 53°N, 54°N and 55°N. The two most dominant species at each site were sampled, yielding a total of twenty-four master chronologies, all of which reflected a highly significant common signal at each site. The chronologies were subjected to a response function analysis to determine the nature of the growth–climate relationships in the region. Summer temperature proved to be the predominant limiting factor with regard to radial growth at most sites. The onset of the optimum temperature regime, however, varies across the network of sites, revealing evidence of a gradient of continentality in the data. Growth–temperature correlations indicated a significant relationship with July temperature at most eastern sites, while western sites tended to correlate with May, June and August temperatures. Central sites tended to correlate with June–July temperatures. We interpret these results as demonstrating the bioclimatic gradient of change between coastally proximal, maritime-influenced sites and inland, continentally influenced locales. This transition occurs approximately 330 km inland from the open Labrador Sea.

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Introduction

Tree rings can serve as reliable proxies for observation of climatic variability (Hughes, 2002), especially where there are limited past climatic information and abundant trees present. A region where dendrochronological analyses should be prominent is Labrador, where both of these conditions are met yet tree-ring studies are few. Schweingruber et al. (1993) included a few tree-ring sites in Labrador in their continent-wide comparison of ring width and maximum latewood density chronologies. D'Arrigo et al. (1996) have used maximum latewood density chronologies from parts of Labrador to reconstruct land and sea surface temperatures for the northwest Atlantic. Tree rings sampled from northern Labrador have also been used to monitor climate variability (D'Arrigo et al., 2003) and the effects of climate change upon latitudinal and altitudinal tree line dynamics in the region (Payette, 2007). Tree-ring data in the form of tramplung scars have also been

used to monitor caribou populations in northeastern Quebec and Labrador (Morneau and Payette, 2000; Boudreau et al., 2003).

To date, however, no systematic analysis has been undertaken to examine the radial growth trends for forests across Labrador. There has also been no significant exploration of the relationship between ring width and climatic variability across the entire region, in either a north–south or east–west direction. It was the purpose of this study to address such a gap in the research by creating master chronologies of the dominant conifer species in central and western Labrador. Moreover, by creating a coordinate-based, systematic sampling network, we seek to lay a foundation for a grid that may be expanded upon in adjacent regions. Such an expanding grid may serve as a powerful tool in spatially analyzing growth dynamics in the broader eastern boreal forest.

A secondary objective of this study was to evaluate the particular spatial trends of the radial growth–climate relationship in Labrador. Labrador is subject to the converging effects of both maritime and continental climatic influences (Rollings, 1997; Roberts et al., 2006) and as such, experiences complex and dynamic bioclimatic interactions (Fig. 1). As climate proxies, tree rings provide us with lengthy records of this growth–climate relationship and, when sampled across a gridded network of sites, may form the

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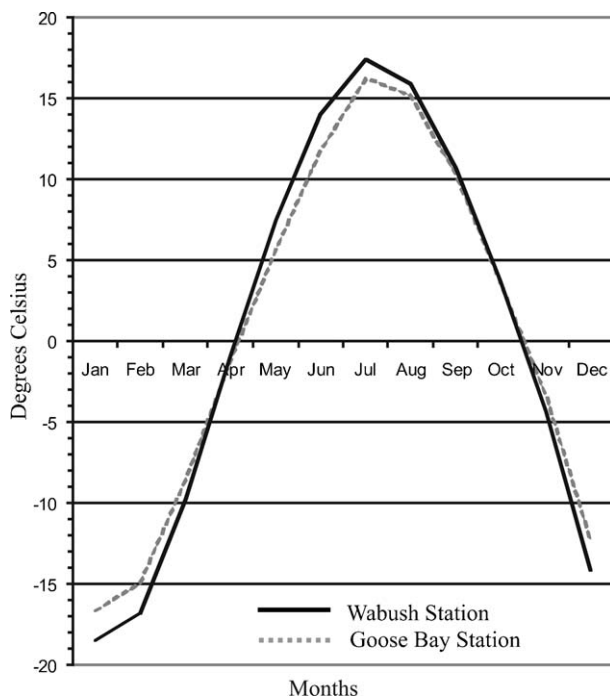


Fig. 1. An example of continentality vs maritime effects illustrated in the historical temperature data from Wabush station, NL (# 8504175) and Goose Bay Station, NL (# 8501900). The inland site (Wabush) is on average colder in the winter and warmer in the summer than the more maritime site illustrated by the data from Goose Bay, even though both sites are at similar latitudes. The data were averaged over the length of the available temperature record and adjusted for elevation.

basis for in-depth spatial analysis across both latitudinal and longitudinal transects. Continentality has been observed by Linderholm et al. (2003), whose tree-ring study of Scots pine in Fennoscandia revealed a gradual transition in the growth–climate relationship across a west to east transect. Similar descriptions of observed continentality in tree-ring networks are seen in the works of Kirchhefer (1999) and Littell et al. (2008), and we seek here to evaluate whether this process can be identified through dendroclimatological analysis in Labrador as well.

Study sites and species

Much of the research into the relationship between climate and tree growth has targeted sites at the limits of conifer growth tolerance (Fritts, 1976; Gedalof and Smith, 2001; Lloyd and Fastie, 2002; Laroque and Smith, 2005), including studies conducted in parts of Labrador (D'Arrigo et al., 1996, 2003). The goal of choosing sites where trees are the most environmentally stressed is to capture a strong growth–climate relationship in the data (Hughes, 2002). The drawback of this approach, however, is the reduced ability of the researcher to demonstrate the spatial variability of this relationship in a systematic way. The rationale of the gridded sampling design presented here is to address such a disadvantage.

A gridded sampling design will allow for a dendrochronological analysis across a broad region such that gradients of change may be more easily observed. Specifically, we have sought to optimize our ability to capture differences in radial growth and growth–climate relationships along latitudinal and longitudinal gradients – an ability that is minimized in studies where individual sites are selected either randomly or at locations targeted for climatic sensitivity.

With this in mind, trees were sampled at twelve remote sites in central and western Labrador along a latitudinal and longitudinal network consisting of three north-to-south transects. Each

transect comprised four sites located at a uniform distance from one another. Study sites were located at the intersection of coordinates formed at 62°W, 64°W and 66°W longitude and at 52°N, 53°N, 54°N and 55°N latitude (Fig. 2). Sampling was conducted as close as possible to these pre-determined grid intersection points, but was subject to some logistical considerations associated with accessing remote locations. When the exact node could not be sampled, a forest setting within five minutes of latitude from each pre-determined node was selected.

The theoretical grid is almost entirely contained within the boundaries of Labrador, though a few of the northern (Lac Indian, Claude Lake) and southern sites (Angie Lake and Petit Lac aux Sauterelles) are found near the Labrador border in Quebec (Fig. 2). From north to south, the grid measures approximately 333 km, while from east to west, the grid measures approximately 256 km and 274 km, respectively, along the north and south boundaries.

Ecoregions that fall within the network of sites include low subarctic forest, mid subarctic forest, high boreal forest and high subarctic tundra (Roberts et al., 2006). The region is dominated by black spruce (*Picea mariana* (Mill.) Britton, Sterns, Poggenb.), with co-dominant species including balsam fir (*Abies balsamea* (L.) Mill.), eastern larch (*Larix laricina* (DuRoi) K. Koch) and white spruce (*Picea glauca* (Moench) Voss) at more northern and eastern sites (Roberts et al., 2006).

Methods

Radial-growth data

Mature trees of dominant or co-dominant size in each forest were selected away from adjacent water bodies or other site inhomogeneities, to minimize aberrant ring patterns within trees. Increment cores were collected from each of the two most dominant conifer species at each site. To form a chronology, a total of 40 cores were collected from 20 trees (two cores from each tree), for each species, at each site. The collection resulted in a total of 480 trees forming 24 chronologies. To check for homogeneity of signal within the ring patterns of each tree, radial-growth measurements were first visually, and then statistically, crossdated using COFECHA (Holmes, 1983). Measurements were standardized using the program ARSTAN (Cook, 1985; version ARSTAN.41d, 03/18/07) to eliminate the biological growth trend during a conservative single detrending procedure, whereby each measurement series was fit with a negative exponential curve, with a default if $k < 0$ to a linear regression of any slope. “Standard” master chronologies were created from the averages of each detrended core at each site. These standard master chronologies were subsequently used to analyze and compare the different chronologies across space and time.

Climate data

Adjusted Historical Canadian Climate Data (AHCCD) were obtained from Environment Canada for the purpose of establishing radial growth–climate relationships for central and western Labrador. Data from the four nearest climate stations – Goose Bay, NL [Station # 8501900], Churchill Falls, NL [Station #s 8501130, 8501131, 8501132], Wabush, NL [Station # 8504175] and Schefferville, QC [Station # 7117825] – were utilized. Monthly temperature and precipitation data were inputs to the response function analysis program DENDROCLIM2002 (Biondi and Waikul, 2004), used to assess the strength of the growth–climate relationships at each of the twelve sites. For this analysis, sample sites were paired with data from the nearest climate station. Radial growth chronologies were analyzed with mean and maximum monthly temperature data and total precipitation data from April of the

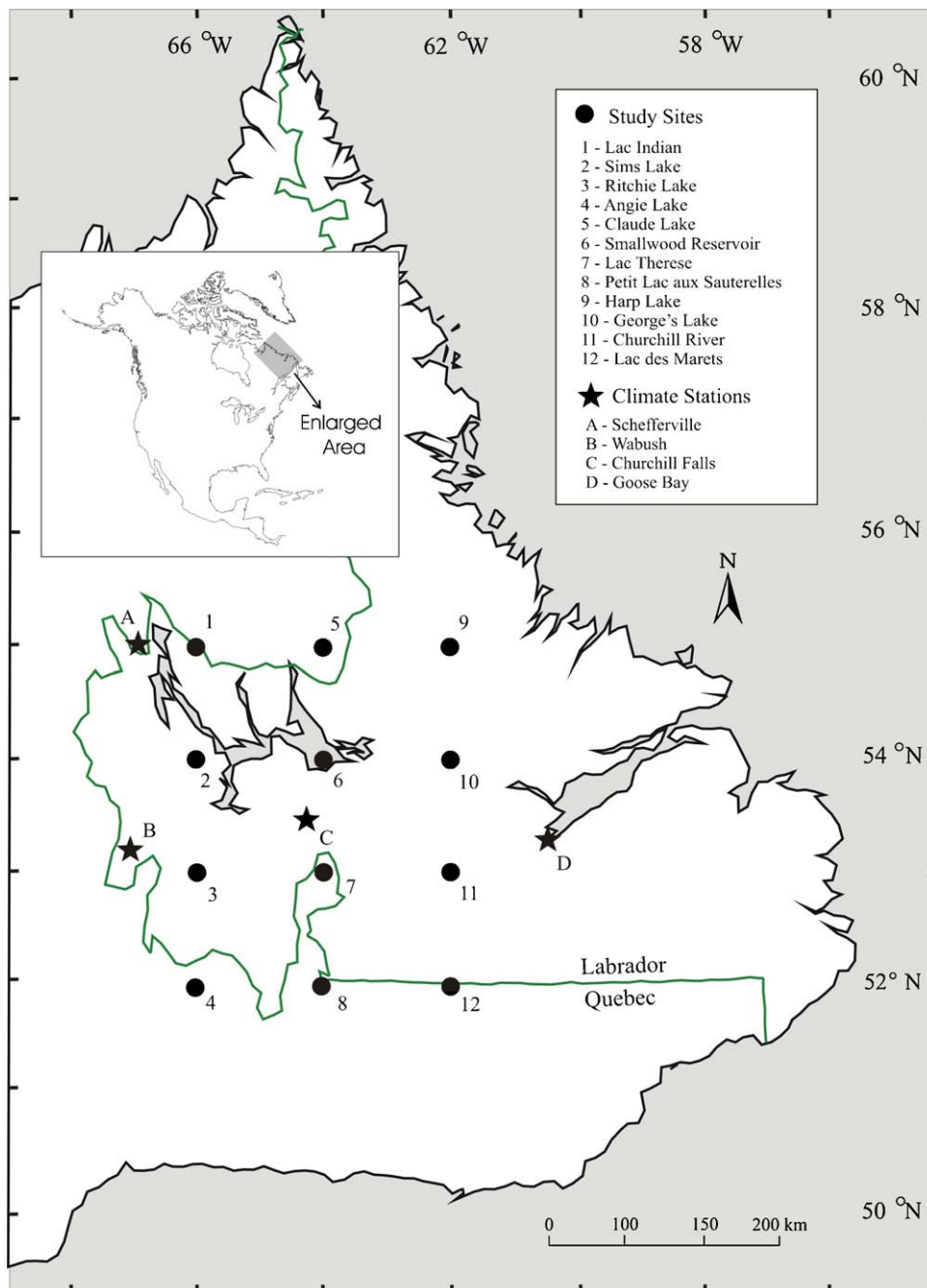


Fig. 2. A map of the study area in western Labrador. The network covers a spatial grid of one degree of latitude \times two degrees of longitude. The four closest long-term climate stations are also marked in relation to the gridded network.

previous year to October of the current year. The time period of the growth–climate analysis conducted for each site equalled the length of the instrumental record of the climate station used. The instrumental records of the climate stations at Goose Bay, Churchill Falls, Wabush and Schefferville were 64, 37, 45 and 58 years, respectively. From this response function analysis, correlation values for each month were obtained and evaluated for statistical significance by the program.

Results

In total, nine black spruce, six balsam fir, six eastern larch and three white spruce chronologies were developed (Table 1). The

average time-span of all chronologies was 186 years, with a mean tree age of 111 years across the entire network (Table 1). The master chronologies demonstrated highly significant series inter-correlations, averaging values of 0.534 – well above the significance threshold of 0.3281 at the 99% confidence interval (Grissino-Mayer, 2001). Eastern larch chronologies illustrated remarkably high series intercorrelation values, with five of six chronologies correlating above 0.600, three of which correlated above 0.700 (Table 1). Balsam fir chronologies correlated, on average (0.459), the lowest (Table 1). All series exhibited strong autocorrelation values, with black spruce generally exhibiting the highest values, and balsam fir and larch slightly lower (Table 1). The mean sensitivity of each chronology indicates that the majority of the species

Table 1
The 24 study sites with sampling information described for each location. Species sampled are abbreviated as follows: BF=balsam fir; BS=black spruce; EL=eastern larch; WS=white spruce. MSI=mean series intercorrelation: indicates homogeneity of signal of trees within the same chronology, based on the mean of all 50-year segments. MTA=mean tree age. MS=average mean sensitivity: indicates sensitivity of trees to annual year-to-year fluctuations in radial growth. AC=unfiltered autocorrelation: indicates the effect of previous year's growth upon current year's growth.

Site name	Species	Latitude (°N)/longitude (°W)	Altitude (m asl)	No. of cores	Chronology time-span (years)	MSI	MTA	MS	AC	
1a	Lac Indian	BS	55°/66°	489	38	1960–2008 (49)	0.583	41	0.175	0.670
1b	Lac Indian	EL	55°/66°	489	39	1864–2008 (145)	0.640	60	0.316	0.750
2a	Sims Lake	BS	54°/66°	484	38	1792–2008 (217)	0.505	141	0.160	0.806
2b	Sims Lake	BF	54°/66°	484	32	1828–2008 (181)	0.498	105	0.176	0.778
3a	Ritchie Lake	BS	53°/66°	566	34	1924–2008 (85)	0.580	65	0.164	0.753
3b	Ritchie Lake	EL	53°/66°	566	37	1907–2008 (102)	0.700	52	0.314	0.715
4a	Angie Lake	BS	52°/66°	644	37	1877–2008 (132)	0.526	108	0.157	0.872
4b	Angie Lake	EL	52°/66°	644	40	1789–2008 (208)	0.753	104	0.333	0.752
5a	Claude Lake	BS	55°/64°	509	40	1764–2007 (244)	0.466	137	0.188	0.760
5b	Claude Lake	EL	55°/64°	509	38	1803–2007 (205)	0.727	112	0.373	0.753
6a	Smallwood Reservoir	BS	54°/64°	467	35	1722–2007 (286)	0.472	186	0.212	0.830
6b	Smallwood Reservoir	EL	54°/64°	467	36	1854–2007 (154)	0.601	112	0.342	0.764
7a	Lac Therese	BS	52°/64°	578	38	1780–2007 (228)	0.522	142	0.189	0.775
7b	Lac Therese	BF	52°/64°	578	38	1819–2007 (189)	0.465	126	0.185	0.772
8a	Petit Lac aux Sauterelles	BS	52°/64°	571	35	1800–2007 (208)	0.407	134	0.182	0.832
8b	Petit Lac aux Sauterelles	EL	52°/64°	571	34	1726–2007 (282)	0.573	143	0.342	0.814
9a	Harp Lake	WS	54°/62°	94	34	1764–2007 (244)	0.500	164	0.188	0.833
9b	Harp Lake	BF	54°/62°	94	36	1851–2007 (157)	0.424	104	0.192	0.778
10a	George's Lake	WS	53°/62°	554	34	1795–2007 (213)	0.502	144	0.193	0.793
10b	George's Lake	BF	53°/62°	554	34	1812–2007 (196)	0.440	111	0.206	0.776
11a	Churchill River	WS	52°/62°	65	37	1643–2007 (365)	0.504	124	0.194	0.779
11b	Churchill River	BF	52°/62°	65	37	1828–2007 (180)	0.516	107	0.186	0.764
12a	Lac des Marets	BS	51°/62°	388	33	1910–2007 (98)	0.504	84	0.156	0.906
12b	Lac des Marets	BF	51°/62°	388	36	1911–2007 (97)	0.411	63	0.153	0.834

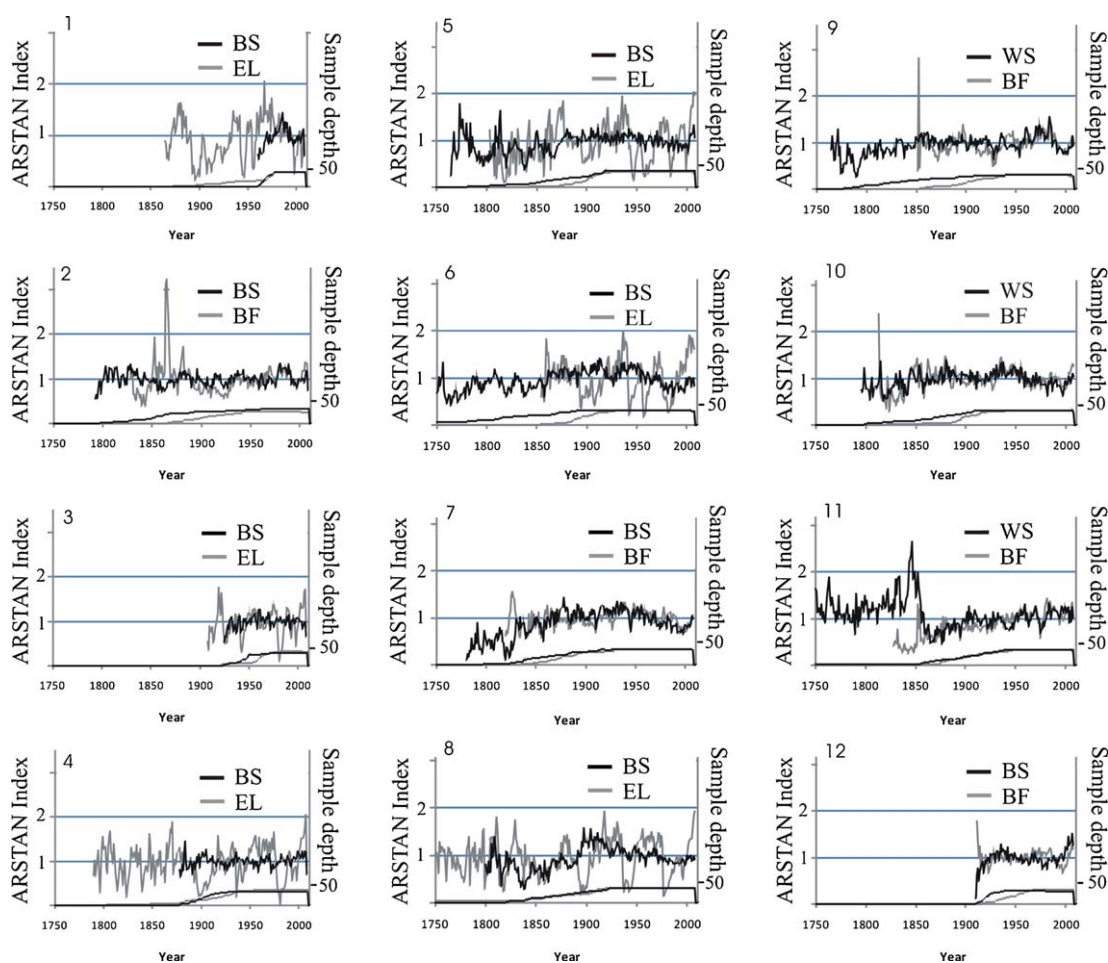


Fig. 3. The 24 chronologies over a 250-year common interval used in this study along with the sample depths at each of the 12 locations. The locations are as follows: (1) Lac Indian, (2) Sims Lake, (3) Ritchie Lake, (4) Angie Lake, (5) Claude Lake, (6) Smallwood Reservoir, (7) Lac Therese, (8) Petit Lac aux Sauterelles, (9) Harp Lake, (10) George's Lake, (11) Churchill River, (12) Lac des Marets. The tree species abbreviations are as follows: BF=balsam fir; BS=black spruce; EL=eastern larch; WS=white spruce.

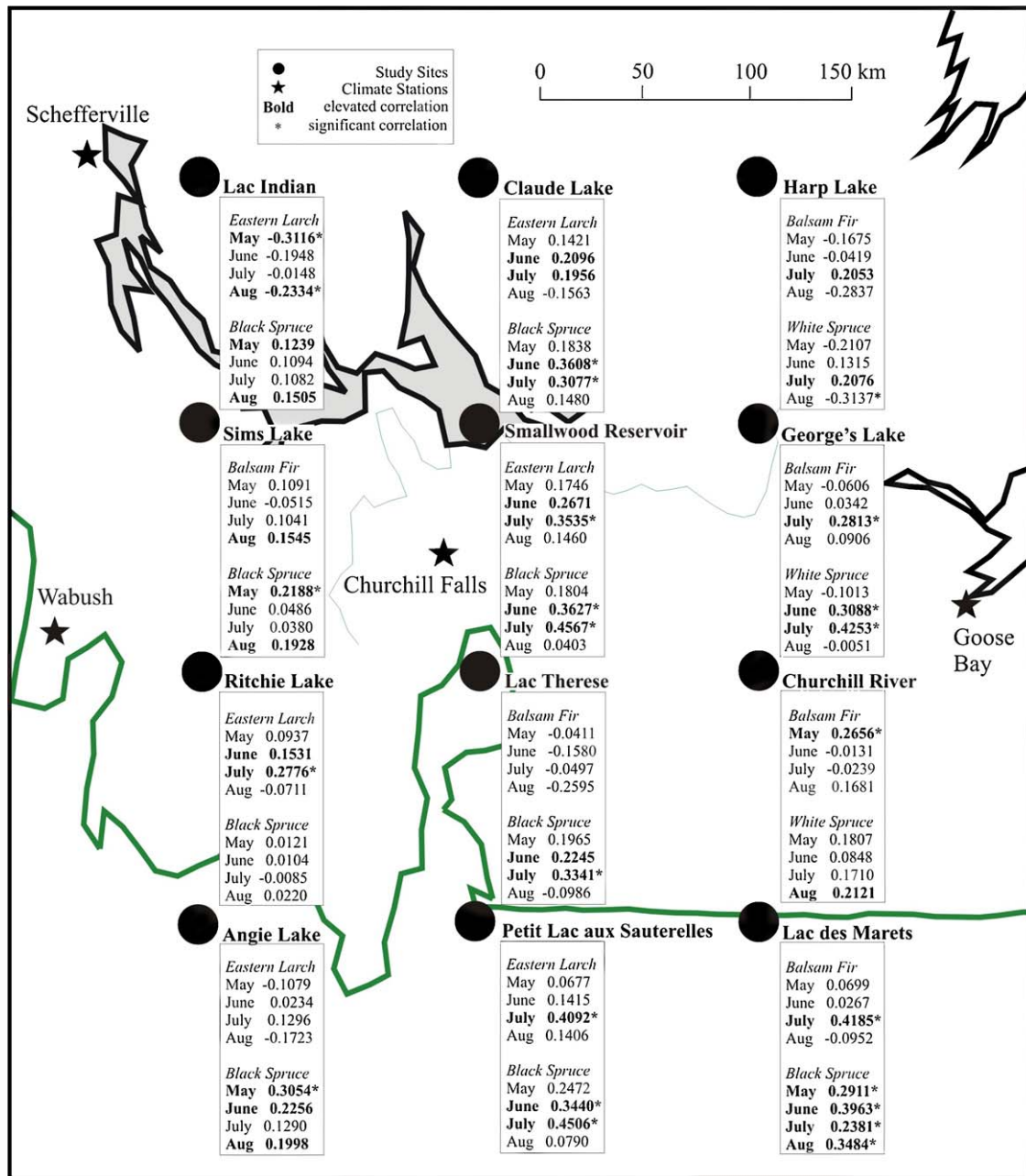


Fig. 4. A map of the gridded network and how each sampled species, at each site, relates to the growing season temperatures from the nearest climate station. Sites are marked by a black circle, climate stations by a black star, and response function correlations to the growing season temperature for each species listed. The response function correlation results display elevated correlation values as bold, while significant correlations (above 95%) are indicated by an asterisk.

are sensitive to the year-to-year fluctuations of their environment (Table 1), with eastern larch illustrating the highest mean sensitivity values, as expected for the deciduous species. The range of values indicate that the black spruce, white spruce, and balsam fir chronologies have low mean sensitivity values, while the eastern larch are considered sensitive (Grissino-Mayer, 2001).

A correlation matrix was constructed to reveal the statistical relationship across common time frames between all chronologies of different species and sites. Of the twelve intra-site correlation values (i.e., different species, same site), the spruce and fir sites exhibited similar radial growth characteristics, whereas the eastern larch chronologies almost always illustrated radial growth characteristics that were dissimilar to the spruce (Fig. 3). As expected, inter-site correlations tended to be higher between chronologies

that were in closer proximity and/or of the same species. Chronologies at Churchill River and Lac Indian were generally found to correlate poorly with chronologies from other sites.

Response function analysis yielded the highest correlation values when radial growth data were compared with summer temperatures. Differences across longitude and latitude are immediately apparent (Fig. 4). The easternmost north-to-south transect (Harp Lake, George's Lake, Churchill River, Lac des Marets) revealed high and/or significant correlations primarily with July temperatures (Fig. 4). The middle north-to-south transect (Claude Lake, Smallwood Reservoir, Lac Therese, Petit Lac aux Sauterelles) show high and/or significant correlations primarily with June/July temperatures (Fig. 4). The westernmost north-to-south transect (Lac Indian, Sims Lake, Ritchie Lake, Angie Lake) indicate high and/or

significant correlations with June and August temperatures (Fig. 4). July temperatures appear to be less correlated with radial growth along this latter transect. Notable exceptions to these observations are once again found at Churchill River (which indicates elevated correlations with August temperature), Sims Lake (which shows elevated correlations with May temperature) and Lac Indian (which correlates poorly with all summer temperature data) (Fig. 4).

Discussion

Results obtained from response function analyses indicate a dynamic growth–climate relationship across central and western Labrador. While it is clear that summer temperatures are positively correlated with conifer growth in this region, the onset of temperatures optimal for radial growth varies across the landscape. Specifically, the timing of significant correlations reflects variation in growth responses as distance from coastal Labrador increases. Correlations at easternmost sites, for example, tend to be highest during the month of July, an outcome that has been similarly found in early results of adjacent network studies in eastern (Dumaresq et al., 2008; Trindade et al., 2008), northern (D'Arrigo et al., 1996, 2003) and southern Labrador (D'Arrigo et al., 1996). Along the westernmost sites, however, the relationship of growth with July mean temperature appears to weaken significantly – if not disappear entirely – while correlations with May, June and August mean temperatures are strengthened. Such a marked temporal difference in the occurrence of increased and/or statistically significant correlations suggests a changing optimal growing temperature regime across a gradient of longitude. While July temperatures at eastern sites are moderated by the influences of a more maritime climate, western sites experience the warm July temperatures associated with a continental climate. As such, increased July temperatures to the west appear to exceed the threshold of positive growth response, resulting in reduced, and in some cases negative, correlation values with the month of July. Subsequently, optimal summer growth regimes to the west appear to straddle the earlier months, with elevated correlations reflected during the months of May, and June and then reappear in August. Sites along the central north-to-south transect illustrate a tendency toward June–July temperature, suggesting a zone where the temperature gradient threshold changes between maritime and continental influences.

Two sample sites – Lac Indian and Churchill River – illustrate trends that depart from the pattern described above. As has been mentioned earlier, radial growth analysis of both sites yielded poor inter-site correlations. For the radial growth data from Lac Indian, the most likely explanation is related to the age of the stand. The mean ages of the larch and black spruce chronologies at Lac Indian are 60 and 41 years, respectively. Young forest stands are strongly influenced by biological competition trends and thus tend to correlate poorly. For the data from the Churchill River site, it is possible that radial growth was influenced by local topography at the sample site. Trees at this site were sampled along a flood plain, which likely resulted in the collection of trees whose growth was strongly and uniquely influenced by the presence of a moisture regime considerably different from the other 11 sites. Such an influence could help explain the delayed onset (i.e., August) of a positive correlation to summer temperature as seen in the location's output. Double detrending of the data from both sites was attempted but had a negligible effect upon the correlations.

Conclusion

The results of this study establish an important starting point for further research into the dynamics of conifer growth over space

and time in central and western Labrador. Robust master chronologies have been created for the four dominant conifer species in this region, documenting a lengthy record of radial growth across a broad region. Furthermore, the systematic nature of this extensive network of sites lays the groundwork for continuous grid expansion through the addition of sites in adjacent regions. Such an expansion will only serve to increase the power of the grid as a tool for spatial analysis.

The results of this study also help to quantify the gradient of continentality that has been assumed to exist in a coastal region such as Labrador, but that has not been well defined. The influences of maritime and continental climates have been found to have dissimilar effects upon tree growth in northern Labrador (Payette, 2007), and it is reasonable that such processes would occur farther south. Response function analysis has revealed a shifting of the longitudinally influenced climatic optimum for conifer growth in central and western Labrador, shedding light upon the complex growth–climate relationship in an under-researched region. Although these effects can be illustrated across transects of longitude, very little difference seems to occur latitudinally in regard to the timing and relationship of the trees to climate. This will have important implications as the climate continues to change in Labrador. Along coastally proximal sites, changes to the optimum growth conditions at the height of summer may prove to have a significant impact on future growth. Continentally proximal sites, meanwhile, may be more greatly impacted by changes to conditions earlier in the summer. In both cases this could have either positive or negative effects on radial growth, depending on when and where the landscape of Labrador warms or cools.

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