

Dendroclimatology, dendroecology and climate change in western Labrador, Canada

by

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Abstract

For the first time, a systematic radial growth analysis was undertaken to determine growth trends of conifers in western Labrador. Dominant and co-dominant species were sampled at 12 sites within a 3 x 4 grid of sites at the intersection of 52°N, 53°N, 54°N and 55°N latitude, and 62°W, 64°W and 66°W longitude. Master chronologies were developed for balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), and eastern larch (*Larix laricina*), producing a total of 24 chronologies. Samples were analyzed to determine the nature of growth-climate relationships in western Labrador, and response function analysis revealed positive growth response to summer temperature. Peak correlation values varied, however, from west to east, suggesting the presence of a gradient of continentality in the data and suggesting that western Labrador is subject to the converging influences of both continental and maritime climate.

Radial growth was also examined for evidence of larch sawfly and spruce budworm outbreaks in the region. Growth reductions in eastern larch host series indicate previous larch sawfly activity as far back as the 18th century, and coincide with reconstructed sawfly outbreaks from adjacent studies. Investigation into past spruce budworm outbreaks are complicated by the absence of a true nonhost species. A new method was attempted whereby host series were compared to same-species regional running mean chronologies acting as nonhosts. Results of this analysis provide convincing evidence of spruce budworm outbreak that parallel outbreak documented in other eastern boreal studies.

The revelation of western Labrador as a region of convergence climatic and disturbance influences provides a unique opportunity for bioclimatic study, particularly within the context of a changing climate. Climatically-influenced natural disturbances such as fire and insect outbreak are reviewed, with emphasis on Labrador and its gradient of continentality. Future climate change in Labrador, likely to be characterized by warmer summers and an eastward expansion of continental influences, may result in reduced growth-temperature correlations at the peak of the growing season.

Additionally, increased summer precipitation will result in reduced fire frequency and subsequently greater influence of insect activity upon the landscape. Imminent climate change will precipitate unprecedented changes to Labrador's forests. Further study is needed as we attempt to gain a more complete understanding of forest dynamics in this under-researched region.

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Statement of Co-authorship

The practical aspects of the research were completed by Peter Nishimura, with logistical support from Colin Laroque and Jennifer Baltzer. All data analysis was completed by Peter Nishimura.

- Manuscript preparation for Chapter 2 (“Observed continentality in radial growth-climate relationships in a twelve site network in western Labrador, Canada”) was completed by Peter Nishimura, with comments and editorial suggestions from Colin Laroque.
- Manuscript preparation for Chapter 3 (“Tree-ring evidence of larch sawfly and spruce budworm outbreaks in western Labrador, Canada”) was completed by Peter Nishimura, with comments and editorial suggestions from Colin Laroque.
- Manuscript preparation for Chapter 4 (“Continentality, disturbance dynamics and potential future implications of climate change based on tree-ring evidence in western Labrador”) was completed by Peter Nishimura, with comments and editorial suggestions from Jenn Baltzer and Colin Laroque.

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To my Mom and Dad

“You will find more in woods than in books;
trees and stones will teach you what you can never learn from masters.”

-St. Bernard of Clairvaux

Chapter 1

Introduction

Climate change in North America has been characterized by a consistent trend of warming since the Little Ice Age (IPCC 2007). Current climate models predict that this trend will indeed continue (Plummer et al. 2006; IPCC 2007), and that anthropogenic forces will accelerate warming to levels that have not been previously experienced (Weber and Flannigan 1997). North American boreal forests, in particular, are expected to be impacted by such warming (IPCC 2007), posing new challenges to forest scientists, managers and policy makers who seek to better understand forest dynamics under the influence of climate. One such area of the boreal forest is that of Labrador, Canada.

Labrador consists of vast boreal forest to the south and tundra to the north, transitioned by forest tundra in its north-central region (Payette 1983). As a relatively undeveloped boreal region (Roberts et al. 2006), Labrador presents a unique opportunity for bioclimatic study. Despite its potential to shed light on climatic influences affecting boreal forest dynamics, it has largely remained under-researched (D'Arrigo et al. 2003).

1.1 Continentality

Labrador is subject to the influences of a continental climate, particularly at its interior (Banfield and Jacobs 1998). As a coastal region, Labrador is also subject to the moderating maritime influences of the Labrador Current (D'Arrigo et al. 2003; Roberts et al. 2006).

Labrador – and perhaps western Labrador in particular – finds itself at a unique junction of these two climatic influences (Rollings 1997; Roberts et al. 2006). The convergence of these influences provides a fascinating opportunity for study regarding the potential presence of a

gradient of increasing or decreasing continental influence across Labrador and how such a gradient might be reflected in bioclimatic interactions.

1.2 Dendroclimatology

Dendroclimatology refers to the dating of annual growth rings as a means to study variability in climate (Fritts 1971). Radial growth in trees is limited by variables such as temperature and precipitation and, consequently, climatic variation is reflected in the growth index of trees. Correlations between radial growth and climatic variables can be obtained through response function analysis, whereby growth-climate correlations are developed and assessed. Such correlations are critical to determining which factors limit growth of a particular species in a particular region. Furthermore, if sample sites are systematically distributed with a broader geographical analysis in mind, then the spatial organization of such correlations can provide valuable information regarding possible gradients of change that exist in the bioclimatic relationship.

1.3 Dendroecology

As a boreal region, western Labrador is not only subject to the influences of climate, but it is also subject to the influences of natural disturbance such as fire and insect outbreak. Fire is the predominant disturbance in North American boreal forests (Rowe and Scotter 1973). It has long affected forest stand structure in the boreal region (Flannigan et al. 2005), and it will surely continue to have a significant influence upon boreal forests. Also of tremendous importance is the impact of insect disturbance upon the forest landscape (Brassard and Chen 2006). There is a long history of insect outbreak in the eastern boreal forest (Coppel and Leius 1955; Blais 1983; Bergeron et al. 2002).

Dendroecology refers to the dating of annual tree-rings to learn about past and present environments (Fritts 1971). In addition to the influence of climate, radial growth in trees is also limited by its biotic and abiotic interactions. Tree-rings provide evidence of growth-limiting influences such as fire and insect activity. This evidence, often in the form of radial growth reductions, can thus be associated with a specific historical time. Historical reconstructions of insect outbreak are a particularly valuable record of the possible changes to forest structure and species distribution, and documentation of their occurrence can provide valuable information about their cause and magnitude. Furthermore, comparisons between the timing of reconstructed outbreaks are important measures of site and regional difference.

1.4 Climate change

In our effort to adequately anticipate climate change and the potential implications such changes would mean for boreal regions such as Labrador, the need for a sound understanding of past and present bioclimatic processes cannot be overstated. Variables such as climate, tree growth, wildfire and insect disturbance are intimately connected, and an awareness of the past and present interactions between these variables can equip us with critical knowledge of how a changing climate may affect Labrador in the future. The dendroclimatological and dendroecological studies presented here offer insight into the nature of these past and present interactions, and provide the basis for a timely consideration of the possible future implications of climate change in Labrador.

1.5 Research objectives and organization of the thesis

The objectives of this research project are to:

- examine the radial growth trends of conifers in western Labrador (Chapter Two)

- analyze the relationship between radial growth and climatic variability, with particular attention to the possible presence of a gradient of shifting continental influence across western Labrador (Chapter Two)
- reconstruct the outbreak history of two known eastern boreal defoliators, larch sawfly (*Pristiphora erichsonii*) and spruce budworm (*Choristoneura fumiferana*) (Chapter Three)
- examine the magnitude and spatial extent of historical insect outbreaks in western Labrador (Chapter Three)
- speculate regarding the potential future implications of forecasted climate change in Labrador, based on tree-ring evidence obtained in its western region (Chapter Four)

Chapter 2

Observed continentality in radial growth-climate relationships

in a twelve site network in western Labrador, Canada

2.1 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*), white spruce (*Picea glauca*), black spruce (*Picea mariana*) and eastern larch (*Larix laricina*) were sampled systematically within a 3 x 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. I 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 kilometres inland from the open Labrador sea.

2.2 Introduction

Tree rings can serve as reliable proxies for observation of climatic variability (Hughes 2002), especially where there is 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, as did D'Arrigo et al. (1992) in their similar study at the North American tree line. 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 trampling scars has 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, I 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 (Figure 2.1). 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 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 I seek here to evaluate whether this process can be identified through dendroclimatological analysis in Labrador as well.

2.3 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; Larocque 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, I have sought to

optimize my 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 (Figure 2.2). 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 predetermined 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 (Figure 2.2). 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*), with co-dominant species including balsam fir (*Abies balsamea*), eastern larch (*Larix laricina*) and white spruce (*Picea glauca*) at more northern and eastern sites (Roberts et al. 2006).

2.4 Methodology

2.4.1 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 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.

2.4.2 Climate data

Adjusted Historical Canadian Climate Data (AHCCD) were obtained from Environment Canada for the purposes 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 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.

2.5 Results

In total, nine black spruce, six balsam fir, six eastern larch and three white spruce chronologies were developed (Table 2.1). The average time-span of all chronologies was 186 years, with a mean tree age of 111 years across the entire network (Table 2.1). The master chronologies demonstrated highly significant series intercorrelations, 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 2.1). Balsam fir chronologies correlated, on average (0.459), the lowest (Table 2.1). All series exhibited strong autocorrelation values, with black spruce generally exhibiting the highest values, and balsam fir and larch slightly lower (Table 2.1). The mean sensitivity of each chronology indicates that the majority of the species are sensitive to the year-to-year fluctuations of their environment (Table 2.1), with eastern larch illustrating the highest mean sensitivity values as expected for the deciduous species. The range of values indicate that the black and white spruce,

and the 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 (Figure 2.3). 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 (Figure 2.4). 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 (Figure 2.4). 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 (Figure 2.4). 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 (Figure 2.4). 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) (Figure 2.4).

2.6 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.

2.7 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 onto 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.

2.8 Acknowledgements

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Table 2.1 - 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	0.753
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

Figure Captions

- Figure 2.1 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 was averaged over the length of the available temperature record and adjusted for elevation.
- Figure 2.2 A map of the study area in western Labrador. The network covers a spatial grid of one degree of latitude x two degrees of longitude. The four closest long-term climate stations are also marked in relation to the gridded network.
- Figure 2.3 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.
- Figure 2.4 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.

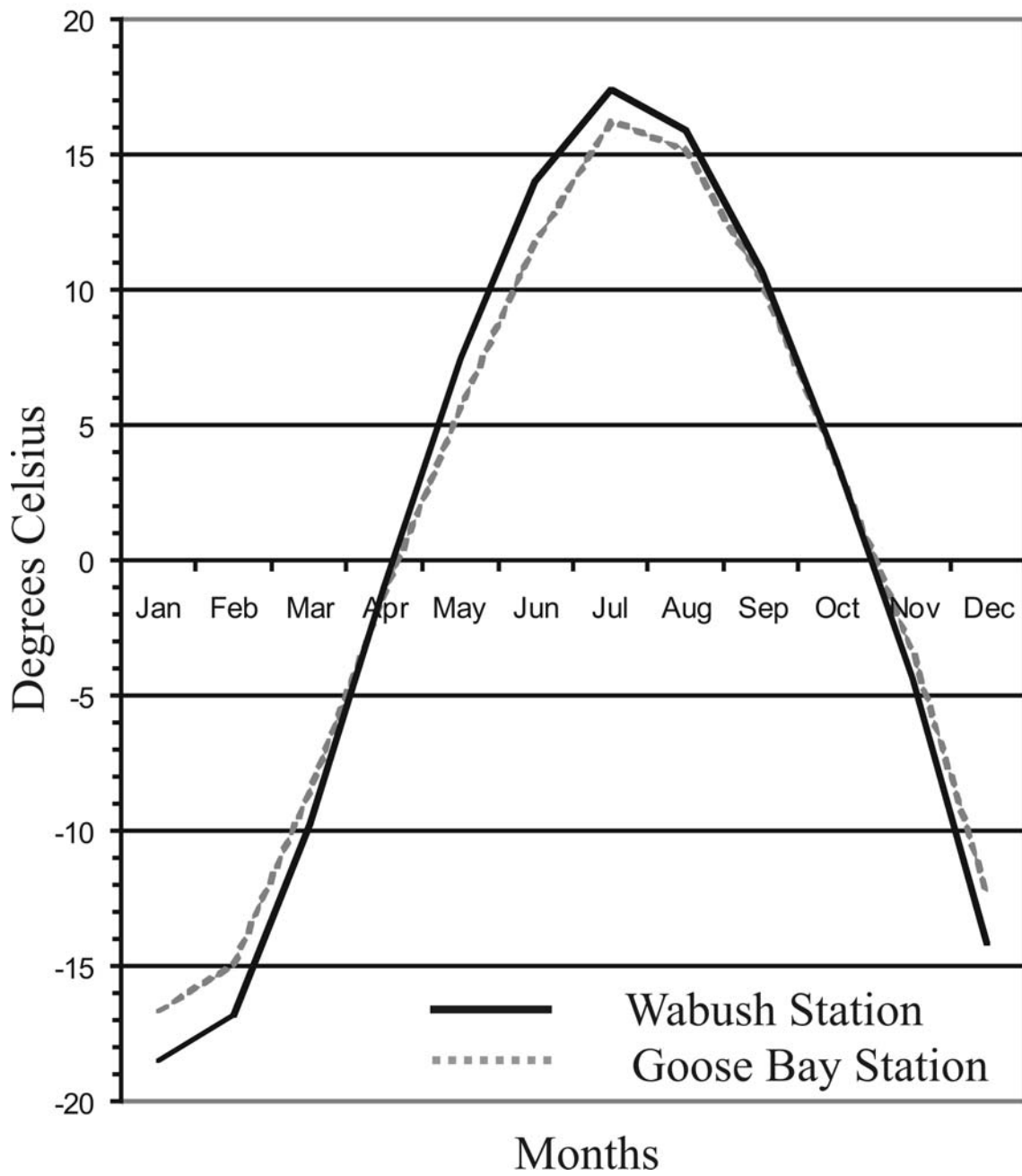


Figure 2.1

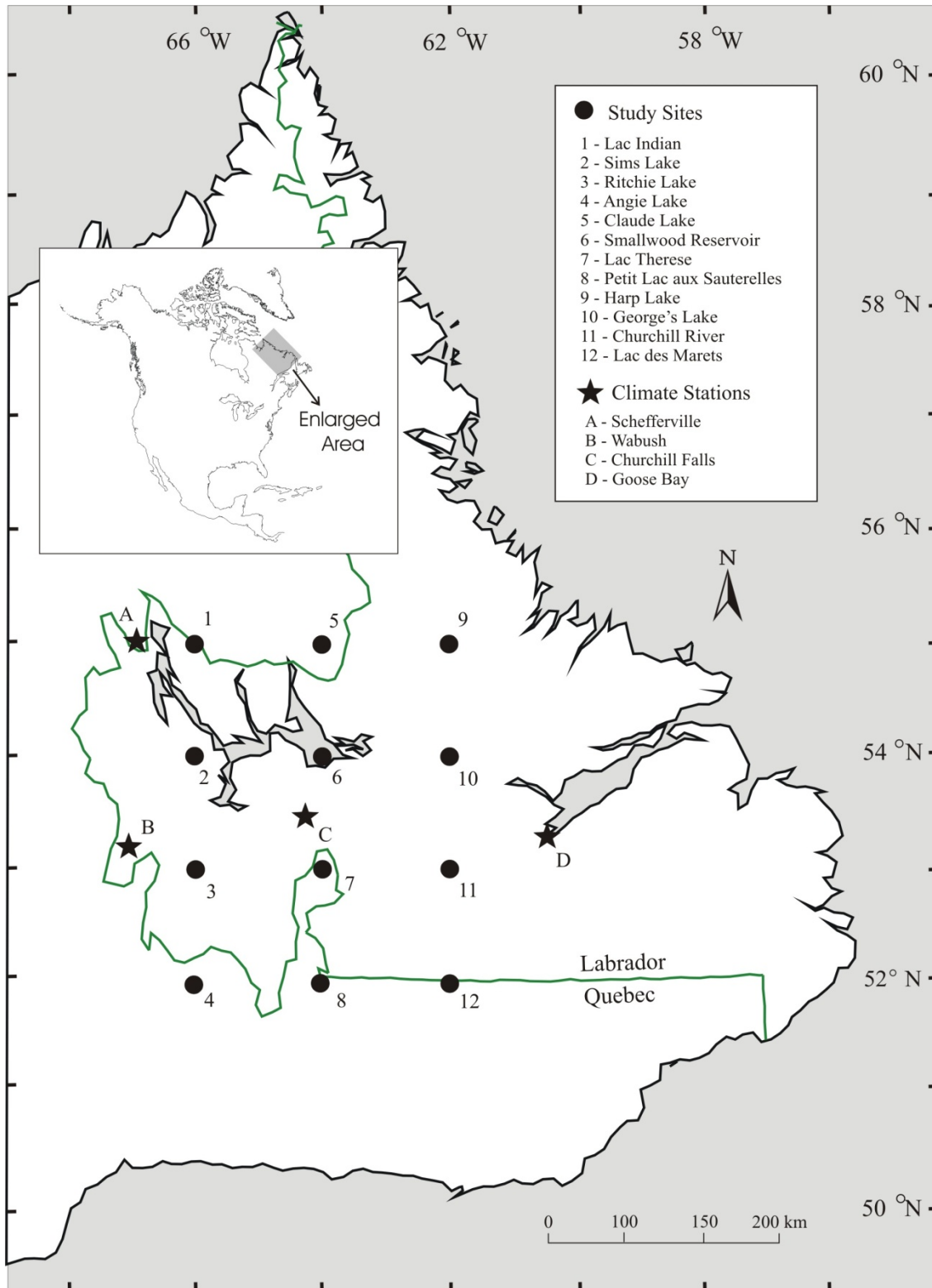


Figure 2.2

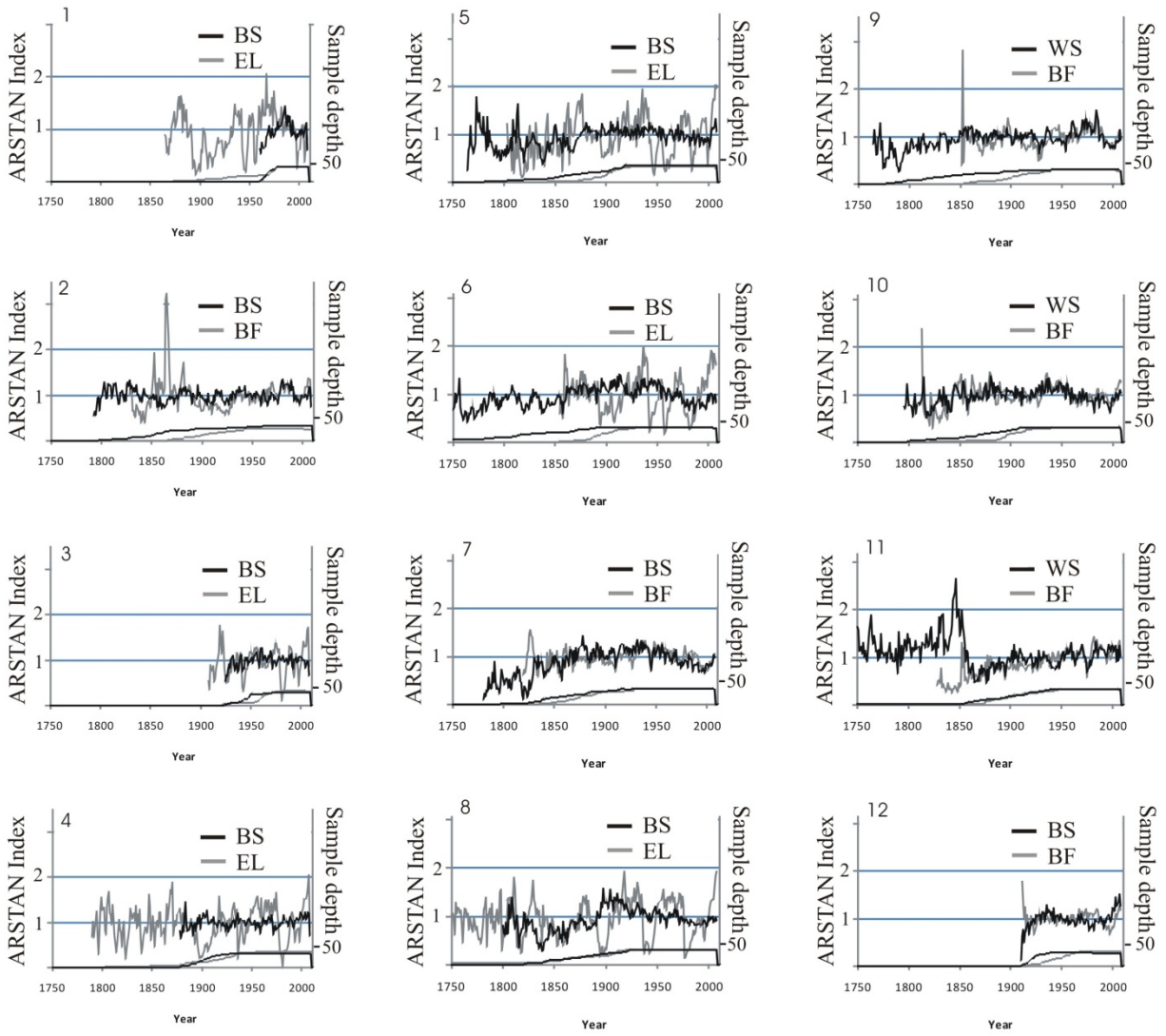


Figure 2.3

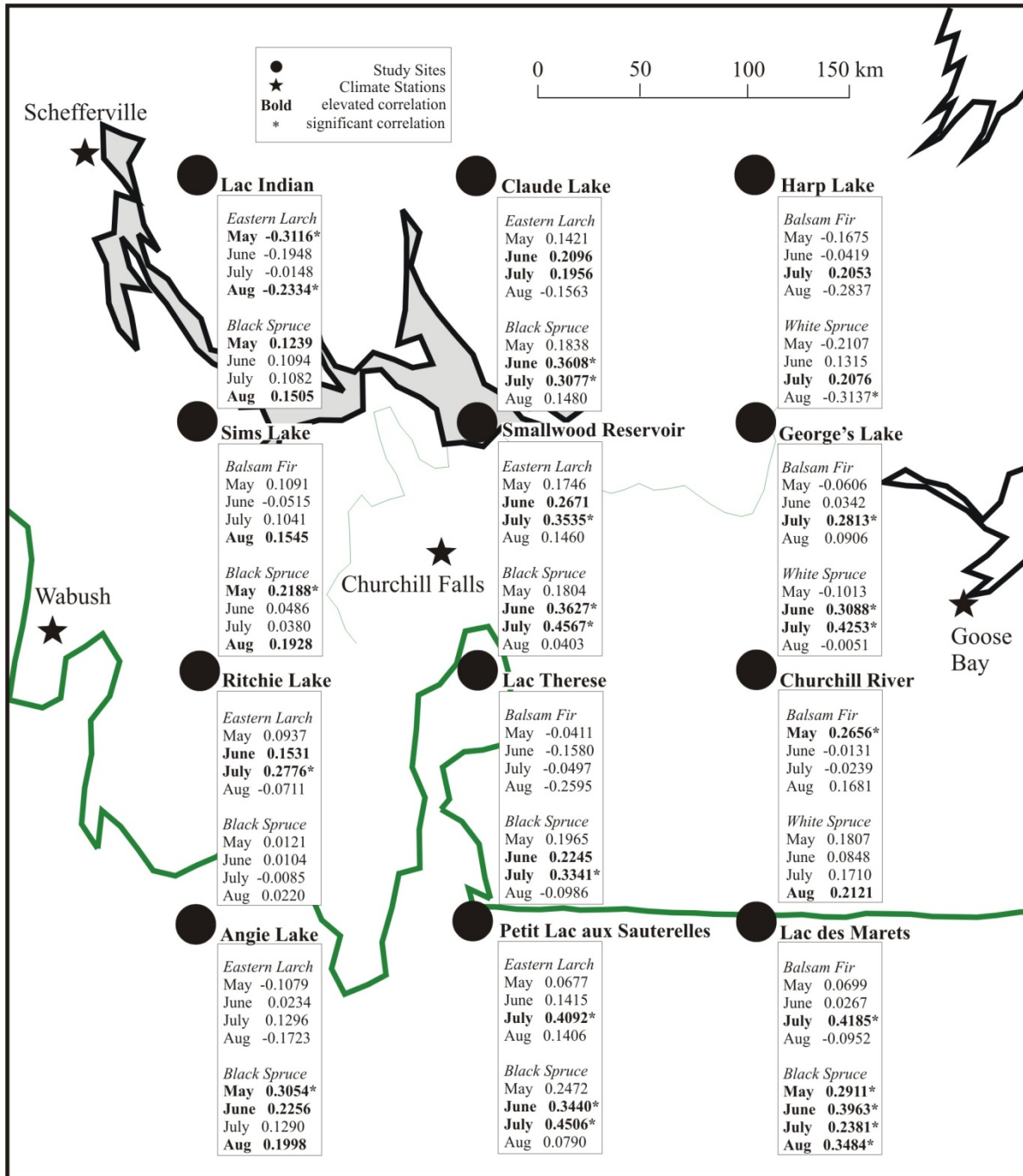


Figure 2.4

Chapter 3

Tree-ring evidence of larch sawfly and spruce budworm outbreaks

in western Labrador, Canada

3.1 Abstract

Much research has been conducted to reconstruct the past insect outbreak history in the eastern boreal region in North America. To date, however, no such research has been conducted in the region of Labrador. In an attempt to reconstruct the history of larch sawfly and spruce budworm outbreaks in western Labrador, systematic sampling was conducted within a 12-site grid. Dominant and co-dominant species were sampled at each site, resulting in 24 master chronologies. Visual analysis of the chronologies and host-nonhost analysis was subsequently conducted. For the host-nonhost analysis of larch sawfly, six eastern larch chronologies (host) and a regional black spruce chronology (nonhost) were used. Regional larch sawfly outbreaks beginning in 1976, 1927 and 1891, as well as localized outbreaks beginning in 1954 and 1877, were identified. Growth suppressions beginning in 1806, 1812, 1752 and 1732 suggest the presence of larch sawfly in North America prior to 1880.

In the absence of a natural nonhost chronology suitable for spruce budworm analysis, a new methodology was developed. For the host-nonhost analysis of spruce budworm, three white spruce chronologies, six balsam fir chronologies and nine black spruce chronologies (host) were compared with regional running-mean chronologies of the same species (nonhost). Growth depressions identified in the 1970s, 1940s/50s, and 1910s/20s coincide with outbreaks recorded in nearby eastern boreal studies, while a suspected outbreak beginning in the early 1890s appears to be specific to Labrador. Localized growth depressions in the 1850s, 1760s and 1750s correspond loosely with outbreaks identified in Quebec. Precise timing and duration of spruce budworm outbreaks is elusive, however I believe that their occurrence can still be identified with confidence. Coincidence of the spruce budworm outbreaks identified here with those documented in adjacent regions helps to validate

the new methodology. In general, insect outbreak in western Labrador appears to be spatially synchronous and regional in scale.

3.2 Introduction

Larch sawfly (*Pristiphora erichsonii*) (Coppel and Leius 1955; Ives 1976) and spruce budworm (*Choristoneura fumiferana*) (Blais 1965; MacLean 1980; Volney and Fleming 2007) are important defoliators in North America's eastern boreal forest. In the eastern boreal forest, larch sawfly targets eastern larch (*Larix laricina*) (Lejeune 1955; Tailleux and Cloutier 1993; Jardon et al. 1994a). Sawfly emerge from May to July, depositing their eggs on newly developed larch shoots on which they feed for several weeks (Lejeune 1955, Ives 1976). Larvae drop to the ground in July and August, spin cocoons, and overwinter before reaching adulthood the following May or June (Lejeune 1955). Host eastern larch respond to defoliation by reducing needle production for the following year, which can in turn inhibit population density (Lejeune 1955). It is due to this ability to produce new foliage each spring that renders the eastern larch remarkably resilient (Graham 1956; Ives and Nairn 1966). While repeated defoliation can result in mortality (Graham 1956), non-mortal infestations result in dramatic decreases in radial growth (Ives and Nairn 1966) and are thus observable in the tree-ring record.

Spruce budworm can also have devastating effects on boreal forest stands, particularly those of balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), red spruce (*Picea rubens*), and black spruce (*Picea mariana*) (Hardy et al. 1983; MacLean 1988). Unlike the sawfly, all life stages of the spruce budworm are restricted to the host tree (Lejeune 1955). Eggs are laid on branches in the middle summer months, after which larvae overwinter and emerge in time to feed on springtime bud development (Nealis and Regniere 2004). Balsam fir and white spruce, whose shoot development outpace that of black spruce, are more susceptible to defoliation (Nealis and Regniere 2004). As with

sawfly-affected eastern larch, fir and spruce reflect infestation in the form of reduced radial growth (Blais 1962).

Defoliation caused by both larch sawfly and spruce budworm can have significant influence on radial growth response (Blais 1965; Swetnam et al. 1985; Bergeron et al. 2002) and thus offers a unique opportunity for study. Dendrochronology is a useful tool in the area of insect outbreak hindcasting, as tree rings can serve as reliable proxies for historical outbreak occurrence (Fritts 1971; Swetnam et al. 1985). In the case of larch sawfly, evidence of outbreaks can be found in the tree-ring record in the form of radial-growth depressions, light latewood rings, and missing or incomplete rings (Harper 1913; Arquilliere et al. 1990; Jardon et al. 1994a, 1994b; Girardin et al. 2001). Similarly, spruce budworm outbreaks can be detected through the identification of radial-growth depressions (Blais 1961, 1962, 1965; Swetnam et al. 1985). Insect outbreaks affecting multiple tree species have also been identified by computer program OUTBREAK (Holmes and Swetnam 1996), wherein an outbreak signature is mathematically deduced through a comparison of host and nonhost tree ring series (Swetnam et al. 1995; Speer et al. 2001).

In the eastern boreal forest, dendrochronological studies attempting to reconstruct the outbreak history of larch sawfly and to study its impacts have been conducted at sites in southern (Krause 1997; Girardin et al. 2001; Bergeron et al. 2002; Girardin et al. 2002; Morin et al. 1993) and northern Quebec (Arquilliere et al. 1990; Tailleux and Cloutier 1993; Jardon et al. 1994a). Attempts using dendrochronology to reconstruct spruce budworm outbreak in Quebec (Blais 1961, 1964, 1965; Morin and Laprise 1990; Morin et al. 1993; Boulanger and Arseneault 2004; Bouchard et al. 2006; Simard et al. 2008), Ontario (Blais 1954), and New England (Blais 1964; Fraver et al. 2007) are more numerous. Each of these localized studies is extremely valuable in our collective attempt to hindcast outbreak occurrence in the eastern boreal forest and, when examined comparatively, they can provide a reliable basis for inferring magnitude at a regional scale.

To date, however, no such study has been conducted in Labrador, Canada. Some historical cartographic representations of spruce budworm defoliation illustrate no record of outbreaks in the region (Brown 1970; Kettela 1983), although a few geographically-limited accounts of Labrador budworm activity have been recorded (Raske et al. 1986; Clarke and Carew 1987). Recent accounts of larch sawfly activity focus primarily on neighbouring Newfoundland (Clarke and Carew 1987), while early documentation of infestation in Labrador is scarce (Fletcher 1906; Coppel and Leius 1955). Bordering the province of Quebec, Labrador has been assumed, perhaps, to have a similar ecological constitution and history to its neighbour to the west. Nevertheless, it remains one of the more under-researched boreal areas (Roberts et al. 2006) and, to my knowledge, no outbreak reconstructions for this region exist. The primary objective of this study was to reconstruct the outbreak history of larch sawfly and spruce budworm in the region of western Labrador. Such a reconstruction could prove extremely useful in helping to determine the scale and degree of synchrony of outbreaks, both locally and when studied in conjunction with other studies in the eastern boreal forest. A secondary objective of this study, then, was to conduct dendrochronological sampling in such a way that inferences regarding the magnitude of insect outbreak could be made at a regional, as opposed to local, scale. Sampling was conducted within a gridded network of sites, thus allowing for a broad spatio-temporal analysis of the data within a single study.

3.3 Methodology

3.3.1 Sampling design and study sites

Dendrochronological sampling for the purposes of insect outbreak analysis in the eastern boreal region has often been limited to a small number of sites within relatively short distance (Girardin et al. 2001; Bergeron et al. 2002; Girardin et al. 2002). Jardon et al. (1994b) sampled across different moisture regimes, while Tailleux and Cloutier (1993) compared coastal sites to a continental site, allowing them to find a spatial gradient within their data. In general, however, any attempt to

draw broader, regional conclusions regarding outbreak history in the eastern boreal region can only be done while considering multiple individual studies in relation to one another. I seek here to conduct a regional analysis within the context of our own sampling grid before continuing on to a broader comparative examination. The ultimate goal of my sampling design was to maximize my ability to capture differences in the occurrence of outbreak across a spatial gradient. Specifically, I have aimed to use a systematic sampling grid as a tool to evaluate the scale or spatial extent of the reconstructed outbreaks.

Accordingly, sampling was conducted at twelve remote sites in central and western Labrador along a latitudinal and longitudinal network (Figure 3.1). Three north-to-south transects at 62°W, 64°W and 66°W longitude consisted of four sites each at 52°N, 53°N, 54°N and 55°N latitude. Sampling was carried out as close as possible to the twelve intersecting points of the grid. Where the logistical challenges of accessing these remote locations prevented sampling at the exact node, a suitable site within five minutes of latitude from each predetermined location was used. The sampling grid is located primarily within the boreal forest zone, though its northern and western sites are found along the border between boreal forest and southern forest tundra zones (Payette 1983). Its forest stands are dominated by black spruce, white spruce, balsam fir, and eastern larch or tamarack (Bearnés 1967).

3.3.2 Development of master chronologies

At each site, mature trees of dominant or co-dominant size were selected for sampling. As much as possible, sampling was conducted away from adjacent water bodies in order to minimize their influence upon the tree ring pattern. Upon visual survey, the two most dominant conifer species at each site were selected for sampling. In order to form a chronology, 40 increment cores from 20 trees (two cores from each tree) were obtained at breast height for each species, at each site. A total of 480

trees were sampled, and radial growth measurements from each core were checked for homogeneity of signal by cross-dating with the program COFECHA (Holmes 1983).

3.3.3 Insect outbreak identification

Initial identification of larch sawfly outbreaks were conducted using a methodology similar to other studies (Harper 1913; Jardon et al. 1994a; Girardin et al. 2001; Case and MacDonald 2003; Girardin et al. 2005). Visual identification of outbreak-associated tree-ring anomalies was performed on each eastern larch series, with specific attention to the criteria established by Harper (1913) and validated by others: (1) the presence of pale latewood in the annual ring of an imminent infestation; (2) a subsequent decrease in radial growth and; (3) an increased incidence of missing or incomplete rings.

In an attempt to better identify occurrences of sawfly outbreak, chronologies were further subjected to a host-nonhost analysis by the program OUTBREAK Version 1.50P (Holmes and Swetnam 1996; Swetnam et al. 1995; Speer et al. 2001). In such an analysis, the host species is compared to a nonhost species that, preferably, demonstrates a similar climate-growth response (Swetnam et al. 1985). Outbreaks are then identified by the occurrence of growth depressions in the host species that are absent in the nonhost species. For my analysis of larch sawfly outbreak, eastern larch chronologies were compared to a regional chronology of black spruce, a reliable nonhost species for larch sawfly outbreak detection (Girardin et al. 2001, 2005; Case and MacDonald 2003). While year-to-year correlations between eastern larch and black spruce were poor, the use of black spruce as a nonhost can be justified on the basis that the two species' radial growth trend well over the long-term (e.g., Figure 3.2 F). The regional chronology was constructed from the nine adjacent black spruce chronologies obtained from the sampling grid. The use of a regional chronology, rather than a same-site chronology, as nonhost was chosen for the reason that finer scale variations present in a same-site nonhost could lead to false identifications of outbreaks. Larch sawfly outbreaks were detected when depressions in the host residual chronology lasted a minimum of four years and where at least one year

occurred below a threshold value of 1.30 standard deviations below the mean ring-width value (calculated to represent the smallest 10th percentile values in the chronology) (Swetnam et al. 1995; Speer et al. 2001). These parameters are comparable to those of similar studies (Girardin et al. 2001, 2005; Case and MacDonald 2003).

To identify occurrences of spruce budworm outbreak, a host-nonhost analysis was also conducted. In this case, however, the selection of a suitable nonhost species was not as straightforward. Spruce budworm can attack more than one species (Blais 1962, 1965; Nealis and Regniere 2004), and often affects, in succession, stands of balsam fir, white spruce, and black spruce (Blais 1962). This “order of preference” relates to the speed of shoot development during the spring season. Balsam fir and white spruce develop shoots rapidly and, as food sources, are thus more susceptible to infestation (Nealis and Regniere 2004). While stands of slower-developing black spruce are less susceptible than balsam fir and white spruce (Nealis and Regniere 2004), however, they can also experience both defoliation and mortality as a result of budworm disturbance.

Previous host-nonhost analyses for spruce budworm have used white and red pine (Blais 1954, 1962, 1964, 1965), northern white cedar (*Thuja occidentalis* L.) (Fraver et al. 2007; Morin et al. 1993), jack pine (Morin and Laprise 1990), and lodgepole pine (*pinus contorta* Dougl. Ex Loud.) (Parish and Antos 2002) as nonhost residual chronologies. In western Labrador, however, all sampling was necessarily limited to the dominant species available: balsam fir, white spruce, black spruce and eastern larch, as none of the previously used nonhost species exist in the region. Consequently, all series with the exception of eastern larch were considered to be susceptible to spruce budworm infestation and hence the development of a reliable nonhost residual chronology became problematic.

Other studies have shown how OUTBREAK analyses can still be conducted successfully where no suitable nonhost was available (Speer et al. 2001; Boulanger and Arseneault 2004). These studies relied upon the availability of historical records in their region of their study sites. In my

study, however, these strategies were impossible as so little has been known or documented with regard to insect outbreak in the remote region of western Labrador. I opted then, to develop a suitable nonhost residual chronology that could be used for spruce budworm outbreak detection at my sites. Nonhost residual chronologies were constructed by compiling balsam fir, white spruce and black spruce master chronologies into three separate regional chronologies. Each regional master chronology (Balsam fir: 0.377, n = 213; White spruce: 0.377, n = 105; Black spruce: 0.411, n = 328) was evaluated for signal homogeneity with program COFECHA using 50-year segments, and each correlated significantly above the 99% confidence interval. In a further effort to filter out the influence of periodic growth reductions, each regional chronology was then converted to a 25-year running mean, or the approximate equivalent to 1.5 times the maximum length of a spruce budworm outbreak. Balsam fir host chronologies were then examined for evidence of budworm-induced growth reduction using a balsam fir “regional running mean” nonhost master chronology. Growth reductions lasting a minimum of 3 years and including at least 1.23 standard deviations from the mean ring-width index were considered to be possible spruce budworm outbreaks. Similarly, white and black spruce host chronologies were compared to white and black spruce regional running mean nonhosts, respectively, with standard deviation thresholds of 1.33 and 1.19, respectively. OUTBREAK results were also considered in conjunction with a visual examination of host and nonhost chronologies. Admittedly, in the absence of a “true” spruce budworm nonhost species, the precise timing and duration of outbreak can only be approximated. The exact timing of spruce budworm outbreaks is problematic to begin with, as growth suppression in balsam fir and white spruce does not correspond precisely with defoliation (Blais 1962). However, the growth signature typically associated with spruce budworm activity remains detectable and I hold that outbreaks can still be identified here with confidence.

3.4 Results and Discussion

3.4.1 Development of Master Chronologies

A total of 24 master chronologies were developed from samples obtained at the 12 sampling sites. Nine black spruce, six balsam fir, six eastern larch and three white spruce chronologies were constructed, each demonstrating highly significant interseries correlations (Chapter Two).

3.4.2 Larch Sawfly

Visual identification of outbreak-associated tree-ring anomalies yielded unexpected results. Pale latewood was identified in 74 of all 240 series (30.8%), but with limited synchrony between series and with little correspondence to the onset of growth suppressions identified here. These results are somewhat similar to those found by Girardin et al. (2005), who observed the presence of pale latewood in only a small proportion of larch series, and which did not coincide well with the growth suppressions they identified. In central Saskatchewan, Case and MacDonald (2003) observed few but consistent occurrences of pale latewood years, and which corresponded well with the onset of their identified sawfly outbreaks. Jardon et al. (1994a) consistently found pale latewood to precede each of their identified outbreaks. Aquilliere et al. (1990), meanwhile, observed evidence of sawfly outbreak in northern Quebec despite observing no defoliation-associated pale latewood at all. In my samples, missing rings were identified in each larch series, with the most frequent occurrences taking place from 1893 to 1901, 1936 to 1947, 1955 to 1958 (observed only at Claude Lake and Smallwood Reservoir), and 1977 to 1984. As many as nine consecutive missing rings were identified, and virtually all missing rings occurred within identified growth suppressions in my larch chronologies.

As noted by Girardin et al. (2005), the limited presence of pale latewood can suggest the absence of large scale outbreaks. Despite the sporadic occurrence of pale latewood in my series, however, the results of my host-nonhost analysis indicate several periods of large-scale or regional larch sawfly outbreaks. Host-nonhost comparison reveals significant and occasionally synchronous

growth suppression in each of the larch series (Figure 3.2). Program OUTBREAK identified several periods of larch sawfly disturbance in the larch series (Figure 3.3), suggesting both regional and localized sawfly outbreak. Three larger, regional outbreaks were observed: from 1891 to 1919, 1927 to 1950, and 1976 to 1985. The first regional outbreak (1891 to 1919) is evident at each of the sites, with the sole exception of Ritchie Lake. The second regional outbreak (1927 to 1950) appears to have had a more lasting impact upon the more northern sites (Lac Indian, Claude Lake, Smallwood Reservoir). The three southernmost (and continentally-influenced) sites at Ritchie Lake, Angie Lake and Petit Lac aux Sauterelles appear to have recovered by around 1945. The third regional outbreak (1976 to 1985) is again observed at five of the six sites, with Lac Indian this time the exception. Two smaller, perhaps more localized outbreaks (1954 to 1970) were also identified. An outbreak from 1954 to 1970 is expressed at the four northernmost sites (Lac Indian, Claude Lake, Ritchie Lake, Smallwood Reservoir), and a small, eastern outbreak (Angie Lake, Claude Lake, Smallwood Reservoir, Petit Lac aux Sauterelles) is observed from 1877 to 1886. Evidence of very early outbreaks at Claude Lake (1806-1811) and Petit Lac aux Sauterelles (1812-1818; 1752-1756; 1732-1741) are also observed.

The timing of these outbreaks coincides to varying degrees with previous Labrador accounts and studies from adjacent regions. As recorded observations of outbreaks in Labrador are few, a comparison with documented and reconstructed infestations in neighbouring Quebec proved useful. The 1976 and 1927 outbreaks coincide roughly with adjacent records from Quebec. In their analysis of shoot scars in larch, Cloutier and Filion (1991) reconstructed sawfly outbreak in northern Quebec beginning in the late 1970s and ending in the mid- to late-1980s. Jardon et al. (1994a) also reported growth depressions from 1984 to 1989. Arquilliere et al. (1990) documents a growth depression from 1940 to 1946, Jardon et al. (1994a) from 1938 to 1952, and Girardin et al. (2001) from 1937 to 1942 and from 1955 to 1962. Filion and Cournoyer (1995) also document a larch sawfly infestation in

subarctic Quebec beginning in 1939. The 1891 outbreak also appears to coincide with previously documented growth suppressions, including overlap with the 1910 outbreak referenced by Coppel and Leius (1955). Jardon et al. (1994a) report growth suppressions in northern Quebec from 1894 to 1906 and 1907 to 1911, the latter of which also coincides with the 1905 to 1908 suppression identified by Arquilliere et al. (1990) in the same region. Girardin et al. (2001) have documented radial growth reduction from 1895 to 1912 in southern Quebec. This supports the hypothesis of an east-to-west migration by the sawfly at the end of the 19th century (Coppel and Leius 1955; Ives 1976). The 1877 outbreak coincides with a similar growth suppression observed by Jardon et al. (1994a) and is likely that to which Fletcher (1906) and Coppel and Leius (1955) have referred. Due to low sample depth, it remains unclear whether the growth suppressions beginning in 1812, 1806, 1752 and 1732 are associated with larch sawfly activity. However, the suppressions identified in 1806 and 1752 do coincide with those documented by Jardon et al. (1994a). In any case, my results both favour the argument that the larch sawfly was active in North America well prior to 1880, and attest to the relatively synchronous wide-spread occurrence of sawfly outbreak in the eastern boreal region.

3.4.3 *Spruce Budworm*

Evidence of spruce budworm infestation was revealed through both OUTBREAK analysis and visual examination of the host and nonhost chronologies (Figures 3.4, 3.5 and 3.6). OUTBREAK results from each host-nonhost analysis suggest regionally synchronous, spruce budworm-induced growth depressions in western Labrador to some degree, though each outbreak is not necessarily evident in each host chronology (Figures 3.7, 3.8 and 3.9). Specifically, some outbreaks were identified consistently within one species but not in another. Balsam fir host chronologies indicate budworm outbreaks peaking in the late 1940s / early 1950s and in the late 1970s (Figure 3.7). These outbreaks are evident at the westernmost (Sims Lake), central (Lac Therese) and easternmost sites (Harp Lake, George Lake, Churchill River, Lac des Marets) across the sampling grid, indicating a

broad, regional impact. Furthermore, these outbreaks have been documented consistently within the eastern boreal region by others (Figure 3.10) (Greenbank 1956; Blais 1961, 1965; MacLean 1984, 1988; Morin and Laprise 1990; Boulanger and Arseneault 2004; Fraver et al. 2007), including Raske et al. (1986), who document a severe outbreak beginning in Newfoundland and Labrador in 1977, and Dobsberger et al. (1983), who report spruce budworm in Newfoundland in the summer of 1982. Absent in OUTBREAK's host-nonhost fir analysis is any indication of the massive spruce budworm outbreak beginning around 1910, reported to have affected areas of Quebec, Maine and New Brunswick (Blais 1961, 1965; Morin and Laprise 1990; Boulanger and Arseneault 2004, Fraver et al. 2007). However, visual examination of the host chronologies does reveal growth depressions in the 1910s and 1920s, particularly at Sims Lake and Harp Lake (Figure 3.4 A and C).

In white spruce host chronologies, the 1970s outbreak is also present at all three sites (Figure 3.5). The data suggest that the 1940s outbreak also impacted white spruce, though to a much lesser extent, at least initially. OUTBREAK results also show white spruce series affected in the mid-19th century, beginning in the 1830s at Harp Lake and George Lake and peaking at all three sites in the late 1850s. These results correspond loosely with the 1832 outbreak identified in southeastern Quebec by Boulanger and Arseneault (2004). Some evidence also exists of an outbreak at Churchill River (beginning in the 1750s) and Harp Lake (beginning in the 1760s), which again align somewhat with Boulanger and Arseneault's (2004) 1752 outbreak, however low sample depth renders my record unreliable. Again absent in the white spruce OUTBREAK results is any indication of the 1910 outbreak, though there is a conspicuous growth depression at Harp Lake in the 1920s (Figure 3.5 D).

In the black spruce chronologies, outbreak identification is less clear. As a tertiary food source, black spruce is not likely to be impacted as severely or consistently as balsam fir and white spruce and thus tree-ring based reconstructions are more challenging. The 1970s outbreak is not apparent in the black spruce host chronologies, with the exception of Lac Indian, Claude Lake and

Smallwood Reservoir, where it is somewhat discernible. This could be a possible indication that the outbreak was more severe at these three northwestern sites. Evidence of the 1940s outbreak can be observed at each of the black spruce sites, most easily at Lac Therese. The 1910 outbreak can be observed in the black spruce host series, peaking around the mid-1920s. Another outbreak, which is not seen in the balsam fir or white spruce chronologies presented here, is visible near the beginning of the 20th century. It appears to begin around the early 1890s and peaks in the early 1900s at all black spruce sites with a sufficiently long tree-ring record, and could be related to an infestation on Cape Breton Island around the same time (Hawboldt 1955, cited in MacLean 1988). Finally, an outbreak appears to begin in the late 1860s, paralleling again the reconstruction in southeastern Quebec (Boulanger and Arseneault 2004). Interestingly, the percentage of affected black spruce series appears to increase during periods of decreased infestation for white spruce and balsam fir (Figures 3.7, 3.8, 3.9). Such a pattern could be an indication of a transitioning food source for the budworm. It is conceivable that during periods where fir and white spruce have become heavily defoliated, that the budworm opt for black spruce as their tertiary food source, thus sustaining themselves until such a time that the fir and white spruce have recovered.

I acknowledge that the use of a regional running mean as a nonhost chronology is imperfect. Evidently, the ideal nonhost chronology is of a species considered not to be susceptible to infestation. In my case, where the only such species (i.e., eastern larch) was greatly influenced by larch sawfly outbreaks, an alternative means of quantitatively identifying spruce budworm outbreaks was necessary. An anticipated challenge to the validity of this method is the question of how climate-induced growth depressions can be distinguished from outbreak-induced depressions. Ideally, the nonhost chronology shares the same climate response as the host chronology, thus allowing for climate-related depressions to be observed in-synch during host-nonhost comparison and thus eliminated as possible outbreaks (Swetnam et al. 1985). While I believe that the parameters used here

in OUTBREAK effectively eliminate the false identification of budworm activity, this technique is somewhat limited, as longer term climatic events such as drought or a pronounced cool period could be mistaken for outbreaks.

Certainly, neither the OUTBREAK analysis with an improvised nonhost chronology nor visual examination of host chronologies alone allow for optimum reconstruction circumstances. However, I contend that these two methods can, in conjunction, still provide valuable evidence of previous spruce budworm activity. I further believe that the methodology and results presented here are ultimately validated when considered within the context of the greater outbreak history of the eastern boreal region. The results of the host-nonhost analysis presented here are not only corroborated by visual detection of radial growth depressions, but they also compare favourably with the results of similar studies. While the absence of a natural non-host chronology has precluded the precise identification of timing and duration of outbreaks, and while there does exist the limited possibility of the misidentification of growth depressions, I consider the case for spruce budworm outbreak during the identified time periods to be strengthened greatly by their alignment with those previously documented in adjacent regions.

3.5 Conclusion

The historical record of larch sawfly and spruce budworm activity in the eastern boreal forest has been well documented. The results presented here offer concrete evidence supporting the long-held assumption that there exists a lengthy and similar history in Labrador as well. Larch sawfly outbreaks beginning in 1891, 1927, and 1976 appear to have been regional in nature, while outbreaks beginning in 1954 and 1877 appear to have been more localized. Growth depressions in the early 1800s, the 1750s and the 1730s lend credence to the theory that the larch sawfly was present in North America prior to 1880. Host-nonhost analysis for spruce budworm suggests that activity in Labrador aligns with that of some parts of adjacent regions. Labrador evidence of budworm outbreaks from

three host species in the late 1970s, late 1940s and 1910-20s parallel documented outbreaks in Quebec and elsewhere. Further evidence of a more localized spruce budworm outbreak beginning near the late 1890s is also visible at all black spruce sites with a sufficiently long tree-ring record. In general, however, impact of insect activity in Labrador appears to be more regional in scale than more localized.

3.6 Acknowledgements

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Figure captions

- Figure 3.1 A map of the study area in western Labrador. The sampling grid consists of 12 study sites. The network covers a spatial grid of one degree of latitude x two degrees of longitude.
- Figure 3.2 Eastern larch series (host) vs black spruce regional master chronology (nonhost). Host series show dramatic and synchronous growth reductions.
- Figure 3.3 Percentage of eastern larch series affected by larch sawfly, by year, with sample depth.
- Figure 3.4 Balsam fir series (host) vs balsam fir 25-year regional running mean (nonhost).
- Figure 3.5 White spruce series (host) vs white spruce 25-year regional running mean (nonhost).
- Figure 3.6 Black spruce series (host) vs black spruce 25-year regional running mean (nonhost).
- Figure 3.7 Percentage of six balsam fir series affected by spruce budworm (left y-axis), by year, as identified by OUTBREAK. Sample depth (right y-axis) is also shown.
- Figure 3.8 Percentage of three white spruce series and three black spruce series affected by spruce budworm (left y-axis), by year, as identified by OUTBREAK. Sample depth (right y-axis) is also shown.
- Figure 3.9 Percentage of six black spruce series affected by spruce budworm (left y-axis), by year, as identified by OUTBREAK. Sample depth (right y-axis) is also shown.
- Figure 3.10 Bar chart comparing results from previous reconstructions in adjacent Quebec with results from the current study. White bars indicate various lengths of tree-ring chronologies, while gray bars indicate identified spruce budworm outbreaks. Hatched bars indicate presumed outbreaks identified from a limited number of samples. (Adapted from Boulanger and Arseneault (2004)).

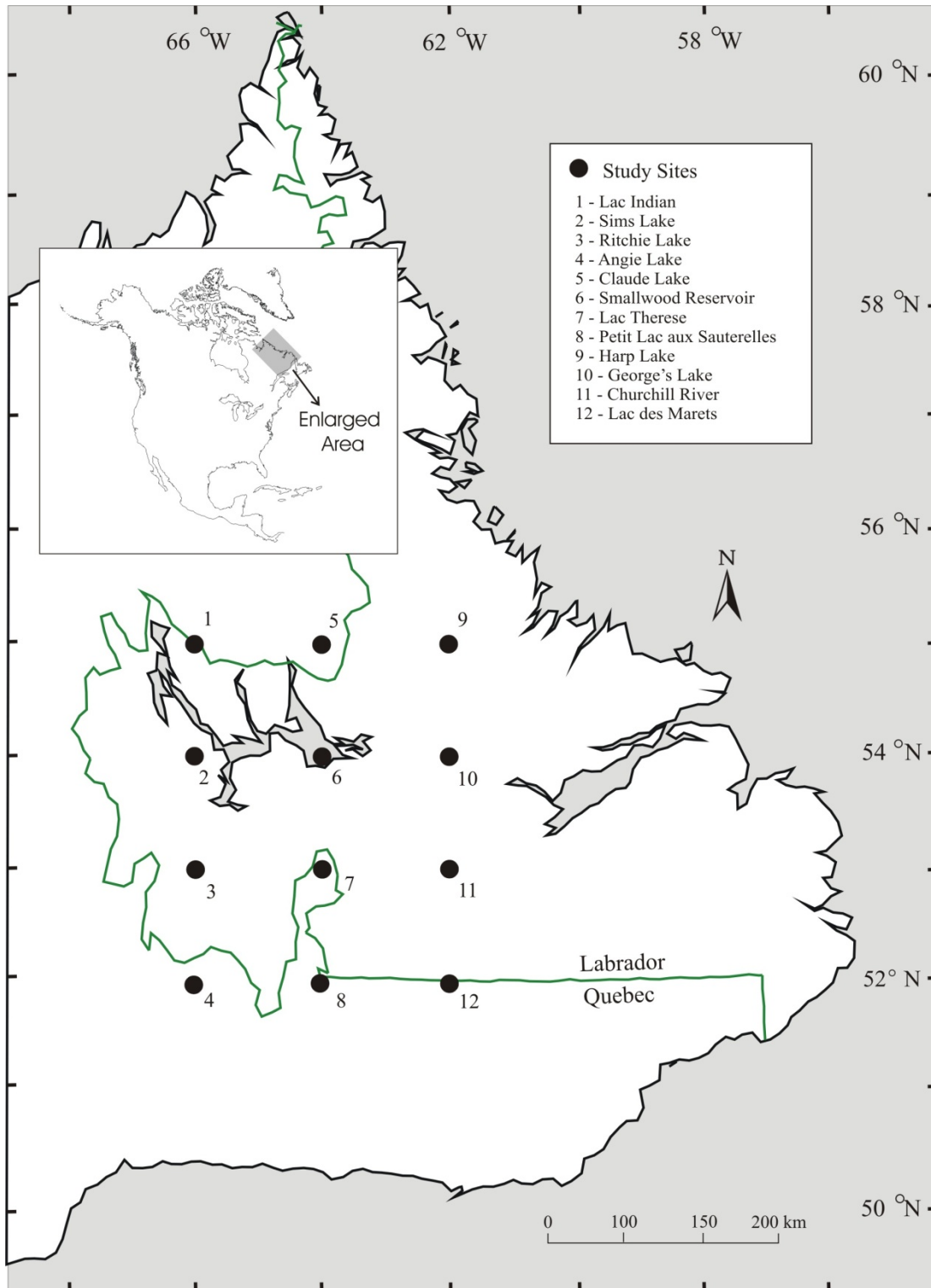


Figure 3.1

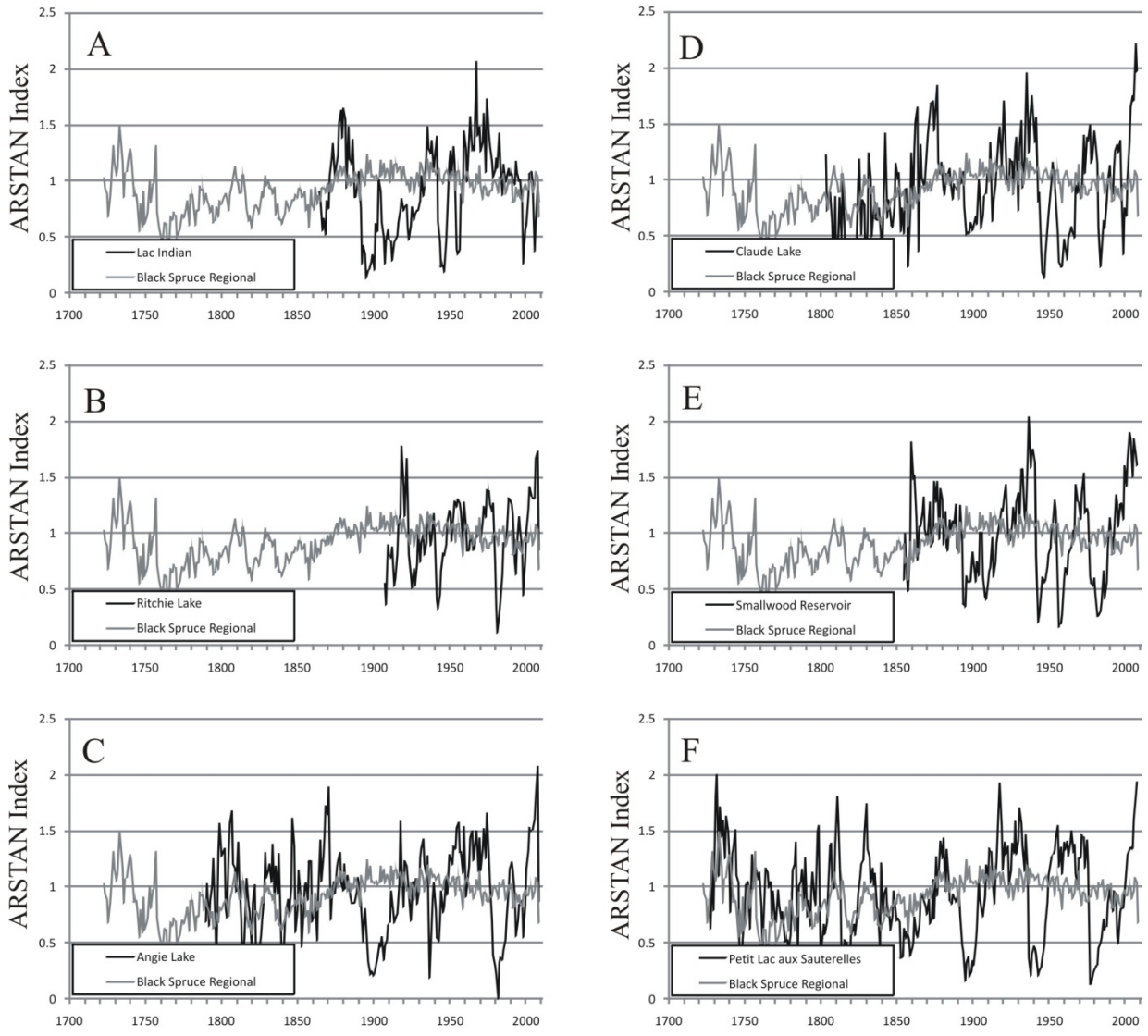


Figure 3.2

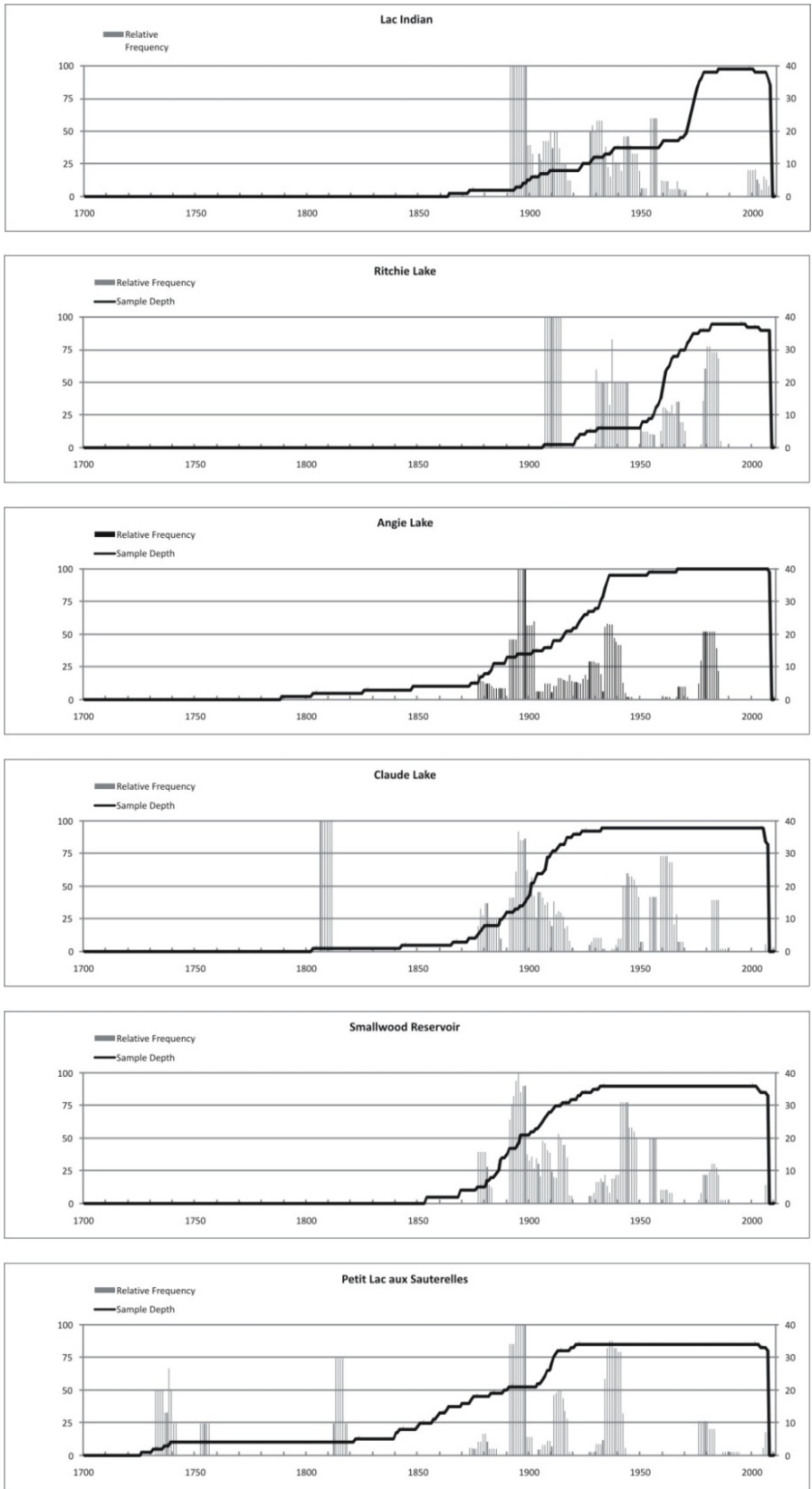


Figure 3.3

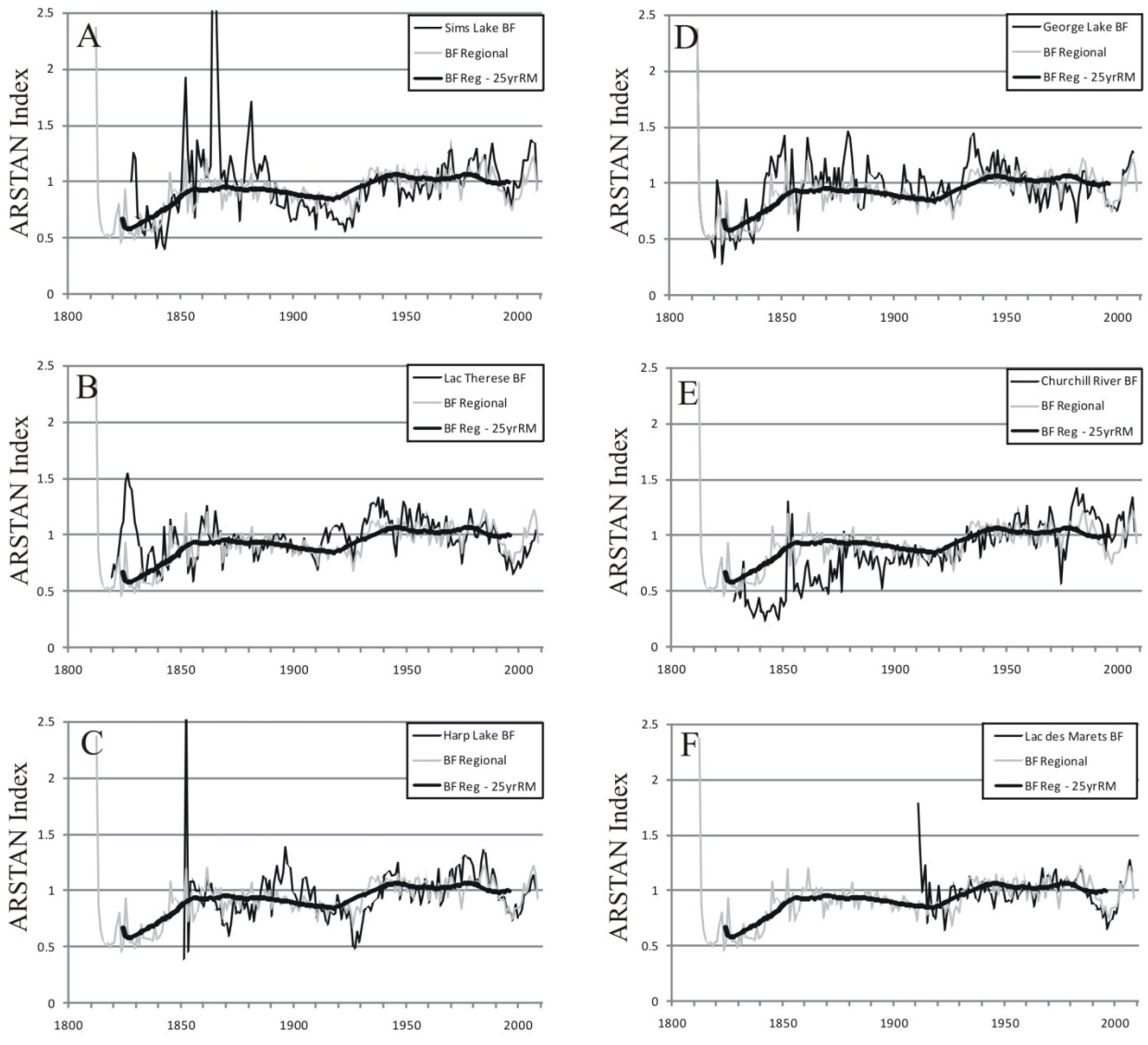


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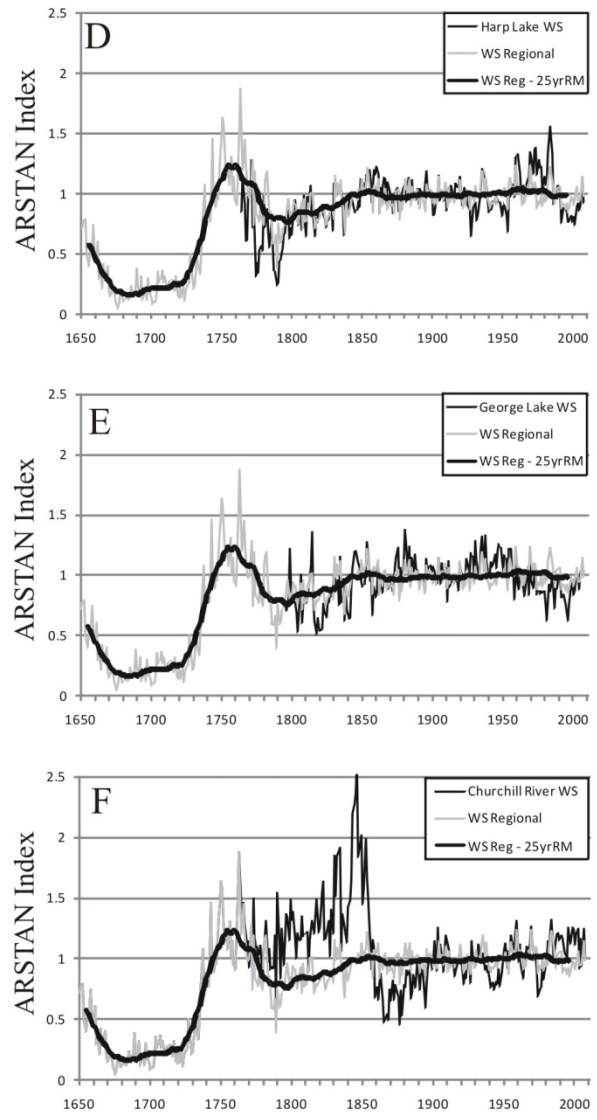
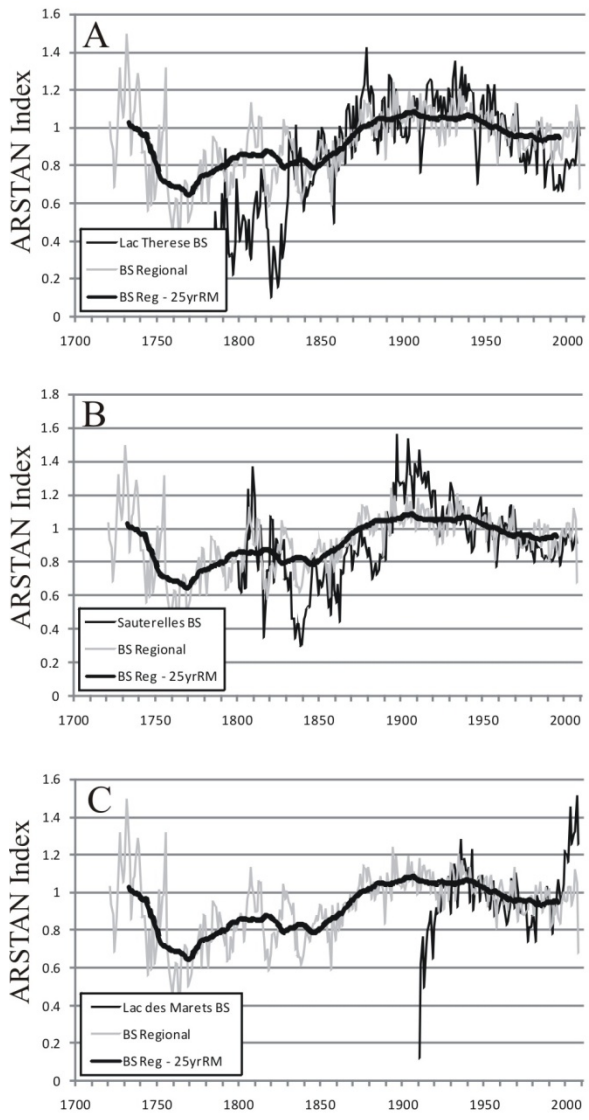


Figure 3.5

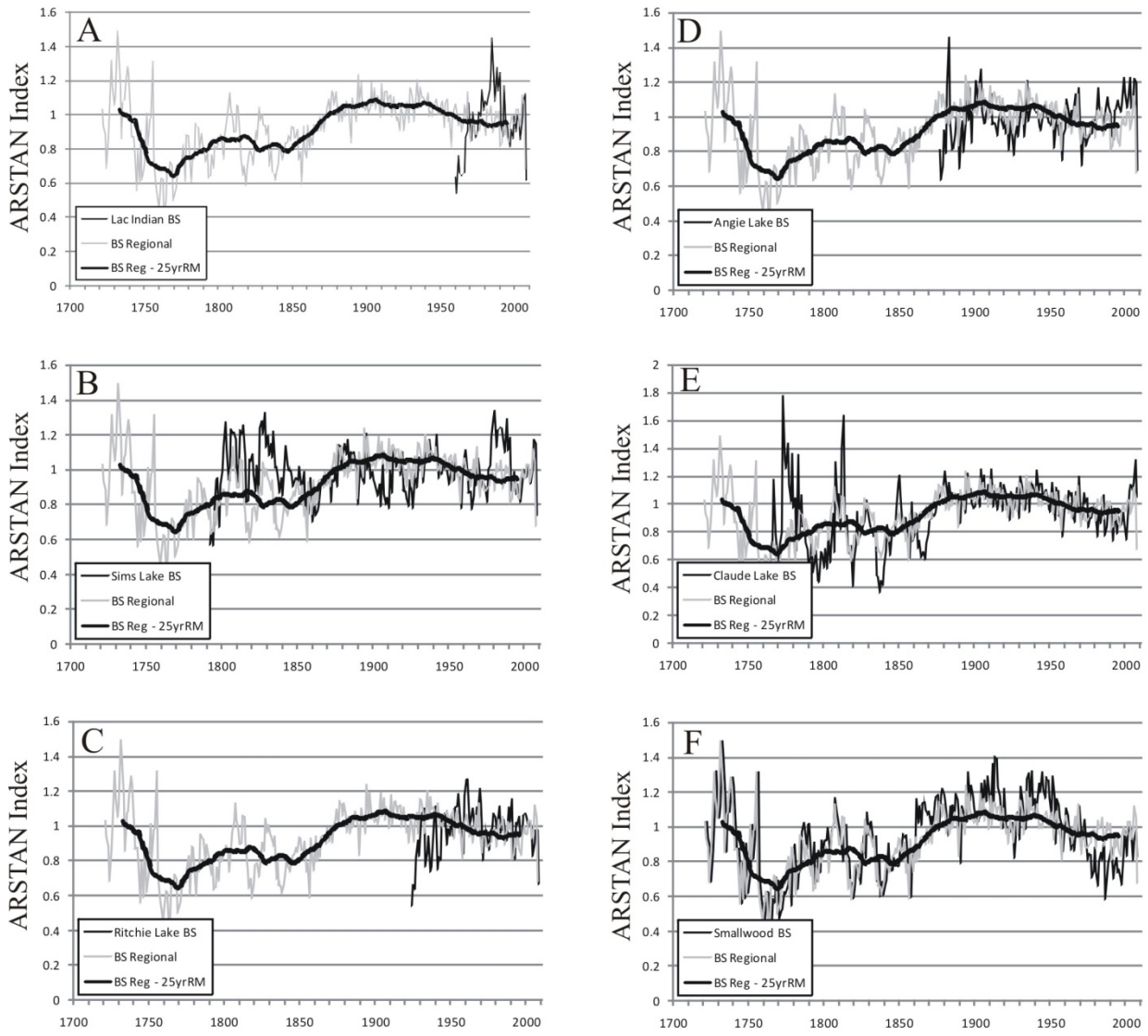


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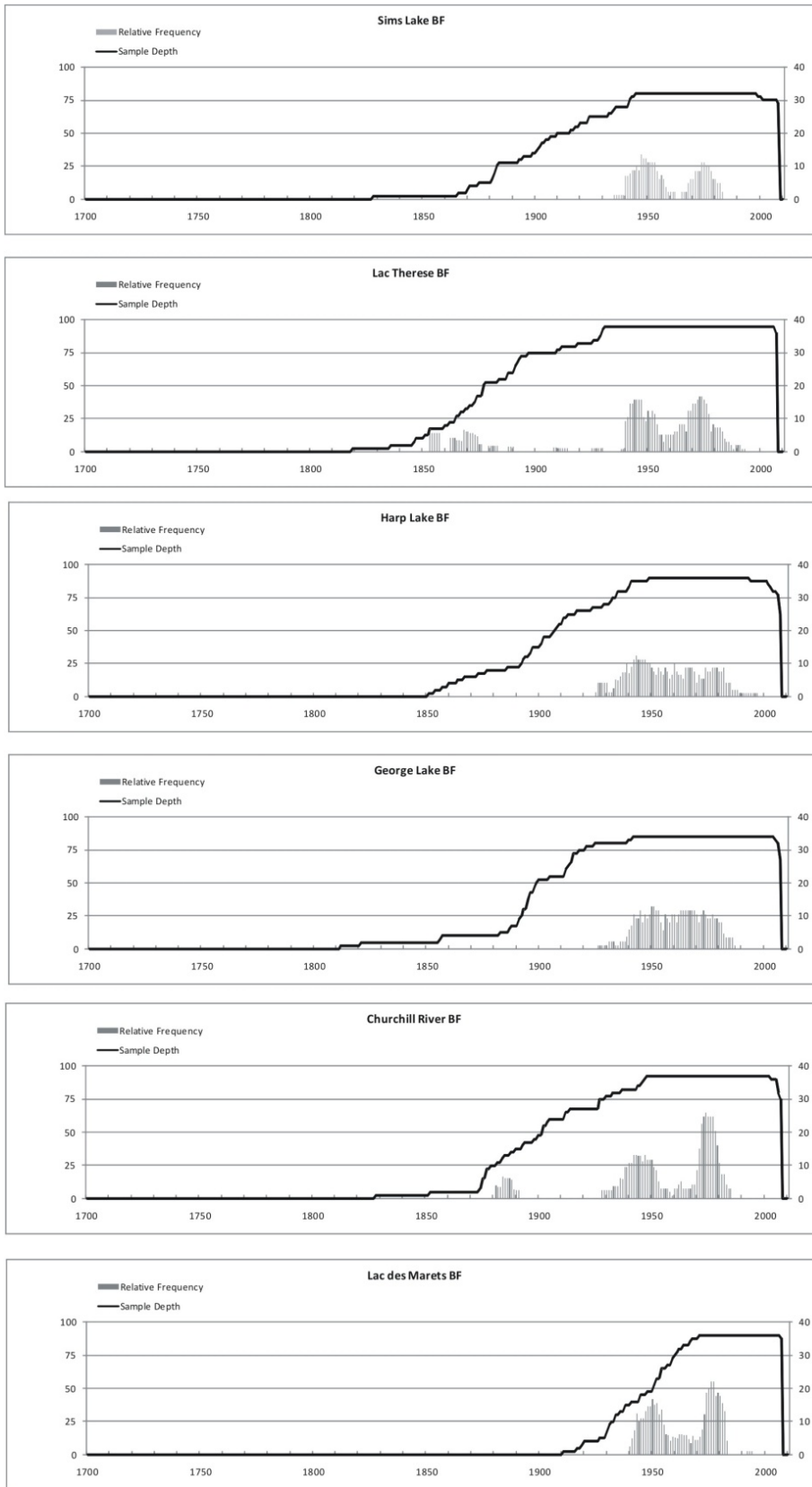


Figure 3.7

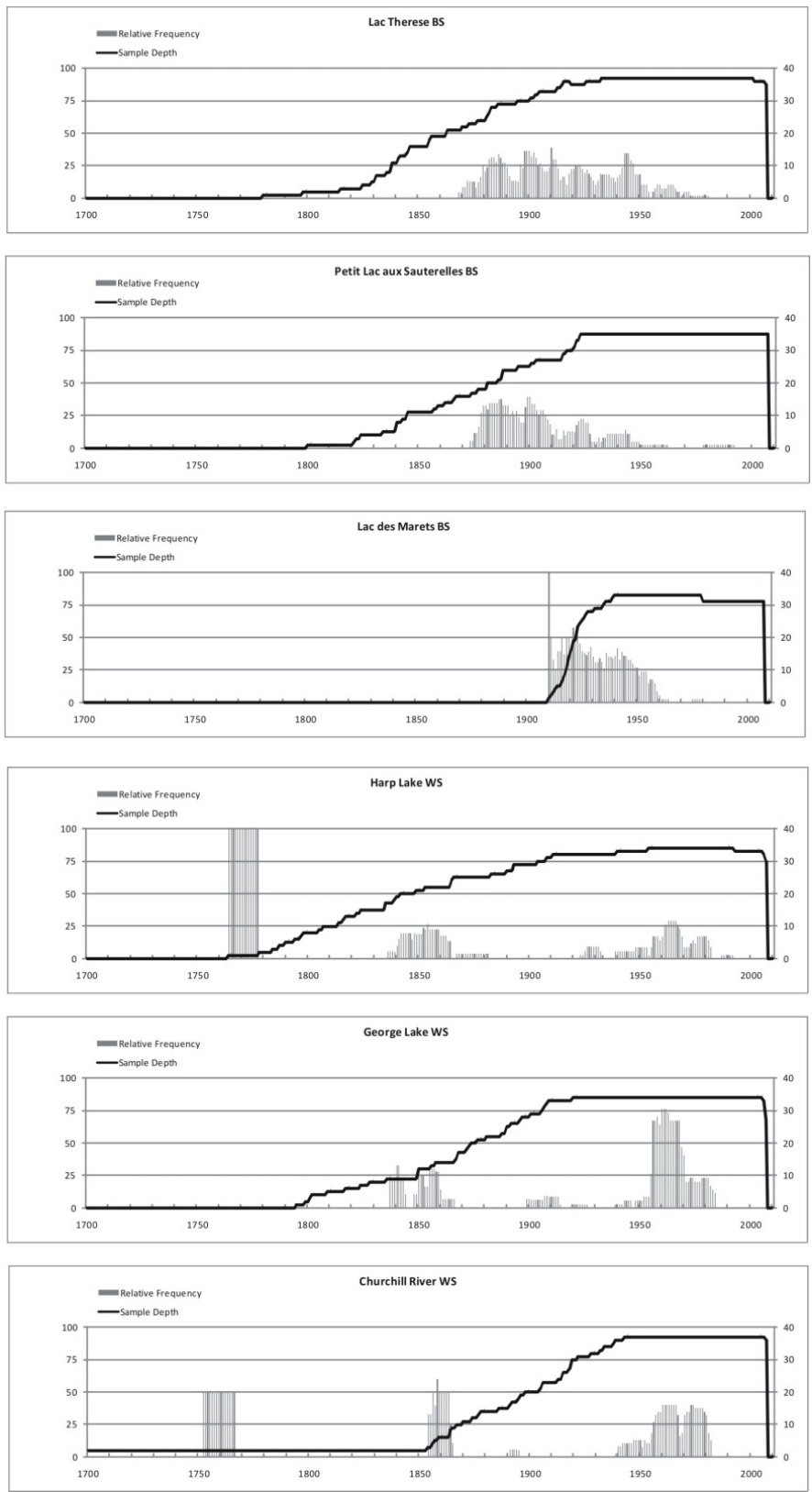


Figure 3.8

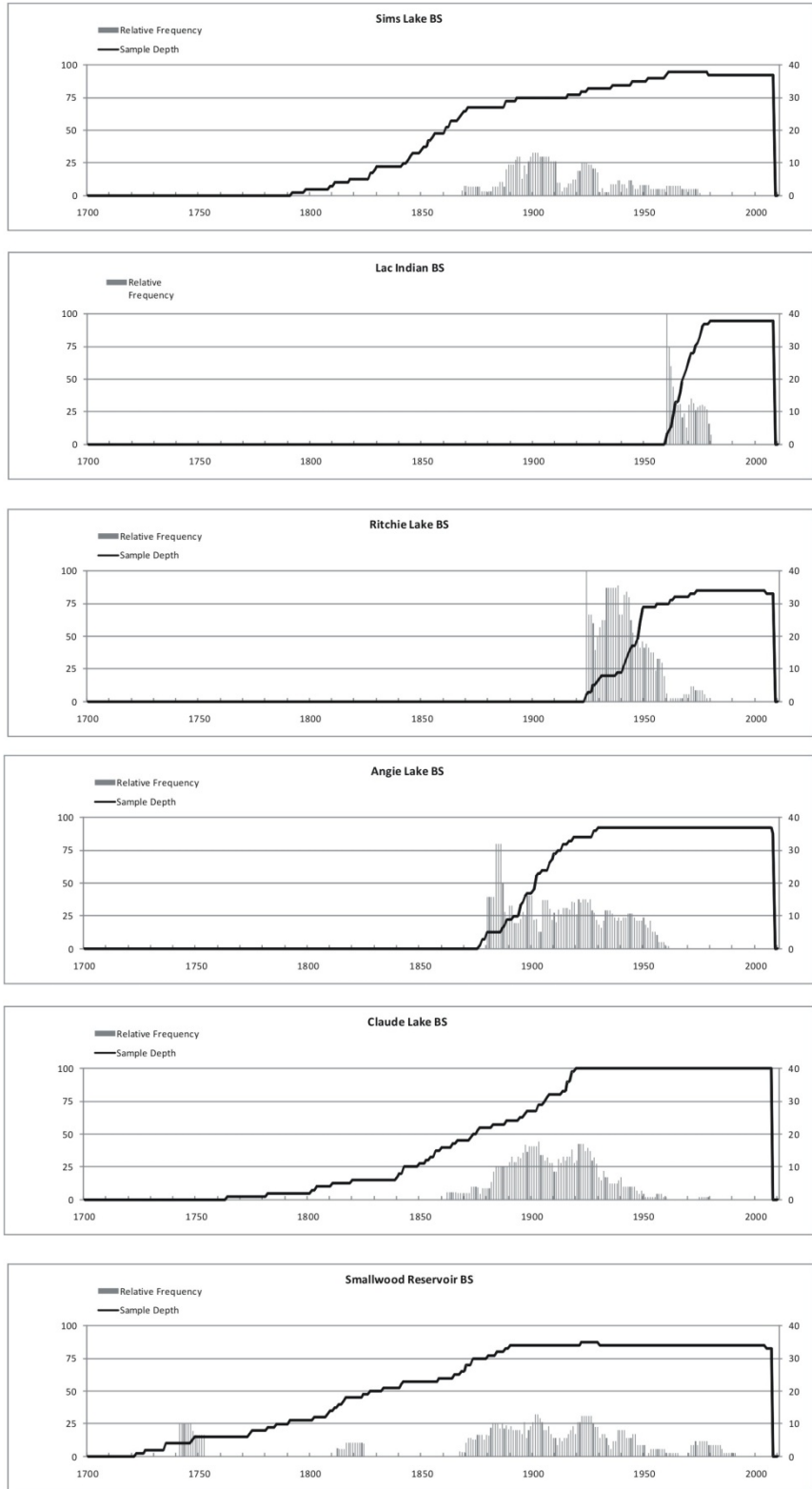


Figure 3.9

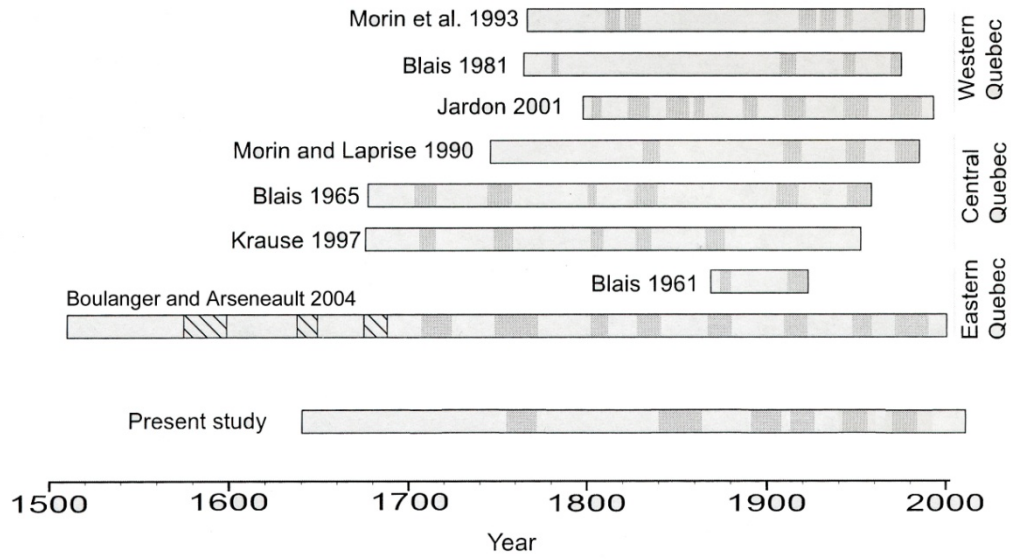


Figure 3.10

Chapter 4

Continentality, natural disturbance dynamics, and potential future implications of climate change based on tree-ring evidence in western Labrador, Canada

4.1 Abstract

Labrador is an eastern boreal region strongly influenced by natural disturbance such as wildfire and insect outbreak. Though knowledge concerning disturbance dynamics in Labrador is limited, an attempt was made to review its fire and insect regimes within the broader boreal context. Labrador appears to have a fire cycle that is long in comparison with the central and western boreal forest, which has important consequences with regard to forest structure, regeneration, succession and the role of non-stand replacing disturbances. Insect outbreak, as revealed by previous historical reconstructions, also consistently plays an influential role in the evolution of Labrador's forests. It has been previously demonstrated through tree-ring evidence that there exists a gradient between continental and maritime climatic influences in western Labrador. Climate change, which is likely to be manifested as an overall warming in Labrador, will introduce a shift in this gradient. Disturbance regimes, which are closely linked to climate, will therefore be affected by this shift, as continental climatic influences move eastward. Warmer summer temperatures may increasingly exceed the threshold for optimum growth, causing a reduced growth-climate correlation at the peak of summer. Insect activity, typically more common at continentally-influenced sites, will likely expand further toward the coast as well. Rapid, unprecedented climate change will require prompt, thoughtful and creative deliberation on the part of forest managers and policy makers in Labrador.

4.2 Introduction

In November 2007, the Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report (AR4), in which it predicted that North American coastal communities and habitats will become “increasingly stressed by climate change impacts” (IPCC 2007). Among those areas facing the impact of intensifying climate change is the Canadian coastal territory of Labrador.

As a boreal region, Labrador is categorized by the IPCC among those particular ecosystems deemed as “likely to be especially affected by climate change”; Labrador is reported as having experienced close to a 1°C increase between 1970-2004, and is further predicted to experience an even more drastic climate change of 3°C to 4.5°C by 2099 (from 1999 levels) (IPCC 2007). Previous studies have already shown that a warming climate will likely have a significant impact upon the boreal forest (Payette et al. 2001; Gamache and Payette 2004, 2005), and in particular upon its fire regime (Carcaillet et al. 2001; Lesieur et al. 2002; Brassard and Chen 2006), which in turn will have important consequences for the greater landscape (Bouchon and Arseneault 2004; Zhang and Chen 2007). Insect regimes and their effects will also be linked to these future variations in climate (Greenbank 1956; Volney and Fleming 2000; Gray 2008) and changes to the fire regime (Aakala et al. 2007; De Grandpre et al. 2000).

While some research has provided evidence of the relationship between Labrador’s tree growth and its climate (D’Arrigo et al. 1996, 2003; Trindade 2009), little research has been conducted thus far with respect to the particular susceptibility of Labrador’s forests to the dramatic climate change proposed by the IPCC. Labrador remains one of the least developed (Roberts et al. 2006) and least researched (D’Arrigo et al. 2003) boreal regions in North America, and therefore presents a unique opportunity for further inquiry and insight into the impacts of climate change upon boreal forest ecology.

Based on what is currently known about Labrador's past and present climate, fire and insect regimes, it is possible to anticipate what changes to its forests could occur as a result of future climate change. As discussed in Chapter Two, climate has significant influence upon tree growth in Labrador and, while much is still to be learned about Labrador's fire regime, fire is certainly a dominant influence upon its landscape and ecology (Richardson 1974). As discussed in Chapter Three, insect disturbance, too, has been shown to have a long and consistent history in western Labrador. Both individually and in combination, climate, fire and insects will have great influence over the future evolution of Labrador's forests.

The objective of this brief assessment is to review recent research regarding the presence of a gradient of continentality in Labrador, and to examine the previous history and current dynamics of fire and insect disturbance in Labrador. I will examine the possible nature of these future climate changes in Labrador, and the potential impacts such forecasted changes would have upon the observed gradient of continentality, the fire regime and the insect regime.

4.3 Continentality

As discussed in Chapter Two, tree-ring data in western Labrador revealed valuable information of the region's dendroclimatology. Radial growth was shown to correlate with summer temperatures and, perhaps more significantly, the spatial distribution of these climate-growth correlations has revealed evidence of a gradient of continentality across western Labrador. The presence of this gradient highlights the sensitivity of the region's trees to small changes in climatic influences such as growing season temperature. Minute differences in temperature (1 – 2°C) across an east to west gradient resulted in marked changes in the growth response of conifers between a moderate, maritime-influenced climate and a more extreme, continentally-influenced climate (Figure 2.1). A changing optimal growing temperature regime was observed across a gradient of longitude whereby the onset of the optimal radial growth coincided with peak growing season temperature (i.e., July) towards the

coast. At inland sites, peak summer temperatures appeared to exceed the threshold of positive growth response, resulting in reduced correlation to temperature. To further illustrate the presence of this gradient, a theoretical, northwest-to-southeast line might be drawn across the region demarcating the apparent separation between more continentally-influenced areas of Labrador from areas that are more maritime-influenced (Figure 4.1). I suggest that any future changes to climate in the region would result in the “movement” of this line of demarcation, which shall be discussed in a later section.

4.4 Fire dynamics

The dominant natural disturbance in the greater circumboreal forest (Flannigan et al. 2006) and the Canadian boreal forest (Bergeron and Dubuc 1989; Amiro et al. 2001) is stand-replacing fire. Labrador’s forests have experienced extensive wildfire activity over the past century (Richardson 1974). Fire is highly influential over Labrador’s phytogeography (Foster 1983, 1984b), vegetation development (Foster 1984a, 1985; Simon and Schwab 2005a; Elson et al. 2007), wildlife species abundance (Simon et al. 2002a, 2002b), as well as stand structure and composition (Roberts et al. 2006; Richardson 1974; Simon and Schwab 2005b; Foster 1984a; Payette 1983).

Of particular help in assessing the impact of fire across a landscape is reference to its fire cycle – a measure of disturbance frequency indicating the period of time (in years) required to burn a total area equivalent to the size of the region in question (Zhang and Chen 2007). Current knowledge regarding the fire cycle in Labrador is primarily limited to studies conducted in its southeastern portion (Richardson 1974; Foster 1983, 1984a, 1984b, 1985, 1986). The uneven age structure of forests in southeastern Labrador and the thickness of the forest floor have been cause to attribute a long fire cycle to that region (Foster 1984a). Disturbance regimes vary across the boreal forest (Brassard and Chen 2006), though time between fires has generally lengthened progressively with climate warming since the Little Ice Age (Drever et al. 2006). The fire cycle in eastern Labrador (~500 years), however, appears to be comparatively longer than the fire cycles in other areas of the boreal forest

(Zhang and Chen 2007), a difference most likely attributable to geographic variations of climate and landscape, if not primarily climate (Carcaillet et al. 2001). Fire cycles can change with latitude, in accordance with climatic and vegetational differences (Payette et al. 1989), and a similar contrast has been noted from east to west across the entire boreal forest (Zhang and Chen 2007).

There exists a clear link between fire and climate (Flannigan et al. 1998; Carcaillet et al. 2001), and between fire and landscape (Zhang and Chen 2007). Indeed, Foster (1983) notes with regard to Labrador that the longer fire cycle might be attributable both to higher precipitation levels and to a landscape (i.e., many lakes, bogs, etc.) that is simply not conducive to widespread and intense fire. Fire cycles in northern, western and central Labrador have not yet been established, though Simon and Schwab (2005b) have suggested that the fire cycle in the central region may be similarly long to that of the southeastern region. As both landscape and climatic influences vary across Labrador, however, a lengthy fire rotation period should not reflexively be applied to each of its regions. Indeed, some limited evidence points to possible variation in fire frequency. Payette et al. (1989), who estimated the fire rotation period (1460 years) at tree line in Quebec's northern forest-tundra, may provide a reference point for the fire regime at the adjacent tree line in Labrador. Fire records in Labrador indicate uneven distribution of fire activity, suggesting local rather than regional meteorological influences (Foster 1983), and Labrador's landscape is by no means homogenous (Roberts et al. 2006). Based on his observation in western Labrador of irregularly-distributed sites of lichen-spruce woodland at various stages of succession, Treter (1995) has suggested regular incidence of fire in that region. Also, two isolated and highly anomalous stands of shade-intolerant jack pine (*Pinus banksiana*) are found in southwestern Labrador within the Redfir Lake-Kapitagas Channel Ecological Reserve (Hare 1950; Parks and Natural Areas Division 1999; Roberts et al. 2006). These are the only known natural stands of jack pine in Labrador (Roberts et al. 2006), and their presence could be an

indication of a shorter fire cycle in the southwestern region (Brassard and Chen 2006; Parks and Natural Areas Division 1999).

Fire rotation period is generally reflected in the forest structure (Arsenault 2001) and composition (De Grandpre et al. 2000), and has a significant impact upon succession dynamics (Bergeron and Dubuc 1989). Labrador's southern forests are dominated by black spruce (*Picea mariana*), which is associated to varying degrees with balsam fir (*Abies balsamea*), white spruce (*Picea glauca*) and eastern larch (*Larix laricina*) (Hare 1950; Roberts et al. 2006). Richardson (1974) reports that post-fire regeneration in Labrador appears to favour the establishment of black spruce over other species such as balsam fir. The capability of black spruce for early post-fire dominance is attributed to its semi-serotinous cone and its ability to produce sufficient seed soon after fire (Viereck and Johnston 1990). Balsam fir seeds and seedlings are often consumed by fire, and delayed post-fire seed production in balsam fir (30 years) further inhibits its establishment and growth (Richardson 1974).

Post-fire establishment of Labrador's black spruce is by no means immediate, however. The post-fire landscape is generally barren of seedlings for the first two or three decades before experiencing only sparse regeneration (Foster 1985). And even while black spruce may enjoy sooner post-fire regeneration than balsam fir, its seed supply is often inadequate for successful establishment (Richardson 1974). Furthermore, southeastern Labrador's cool, moist climate has proven to be highly conducive to the process of paludification (Foster 1984b) whereby, as the forest ages in the absence of fire and presence of precipitation, the forest floor thickens to such a point that there occurs a gradual rise in the water table (Fenton & Bergeron 2006). This process typically is held in check by fire disturbance which, if sufficiently intense, is highly effective at slowing or eliminating the accumulation of soil organic matter on the forest floor (Simard et al. 2007). Such accumulation would otherwise impair seedbed conditions (Richardson 1974), which in turn have a significant impact upon

long-term stand development (Arsenault 2001). This is particularly evident in areas where fire frequency is low (Brassard and Chen 2006). In southeastern Labrador, the long fire cycle and subsequent accumulation of organic material is an impediment to seed growth, resulting in slowed, limited or even no regeneration (Foster 1984b, 1985, Richardson 1974). In northern Labrador, a fire event can be particularly devastating. Stunted black spruce krummholz are incapable of producing any significant amount of viable seed, thus limiting and even preventing post-fire regeneration (Payette 1983; Arsenault and Payette 1992). Such post-fire spruce exclusion can have further ecological consequences through decreased snow cover and subsequent changes to the soil profile (Arsenault and Payette 1992).

Studies in the area of succession dynamics specific to Labrador are limited. Treter (1992) has reconstructed a 315-year vegetation chronosequence in central Labrador in which he describes the most important vegetational changes as occurring within the first 100 years after fire. He observes that sexual regeneration among spruce seedlings occurs between 10-15 years during post-fire recovery, with the greater recovery period taking place over 30-40 years while ground vegetation remains relatively undeveloped. Foster (1985) documents a slow and uneven reforestation process (70-100 years) of black spruce and balsam fir in southeastern Labrador, with a landscape dominated by lichen-woodland. Simon and Schwab (2005a) show similar succession patterns in western Labrador, citing the influence of a cold climate in addition to the poor seedbed conditions revealed by Foster and Richardson on the coast. They further noted the association of balsam fir and white spruce with older (~140 year) burn sites. Stands in the northeastern boreal forest of Quebec have shown similar post-fire dominance by black spruce and subsequent succession (>100 yrs) towards balsam fir dominance or spruce-fir dominance in the absence of fire (De Grandpre et al. 2000).

4.5 Insect dynamics

Insect outbreak constitutes a major influence over the boreal forest (Brassard and Chen 2006), and can lead to high levels of defoliation and mortality given the right combination of population, climate and site conditions (Tkacz et al. 2008). As with the fire regime, little is yet known about specific insect dynamics in Labrador. Labrador's forest stands are dominated by black spruce, white spruce and balsam fir (Bearnès 1967), each of which are susceptible to budworm attack, though the latter tends to experience the most devastating defoliation (Royama 1984; Nealis and Regniere 2004). Budworm attack tends to target balsam fir, then white spruce, as primary food sources, a preference that seems to be related to the timing of shoot development in the host tree (Nealis and Regniere 2004). The post-outbreak environment is not conducive to white spruce regeneration (Bergeron and Dubuc 1989), thus diminishing its presence within the affected stand (Brassard and Chen 2006). Eastern larch – host species for the larch sawfly – is also found in abundance, particularly in western Labrador.

Sawfly outbreak studies specific to Labrador are limited. Fletcher (1906) reports larch sawfly activity in the late 19th century, while Coppel and Leius (1955) cite the accounts of Hewitt (1912) and Brown (1939), who describe sawfly activity in 1910 and 1939, respectively. As reported in Chapter Three, tree-rings have provided evidence of historical spruce budworm and larch sawfly activity in western Labrador. Strong evidence of spruce budworm outbreak exists, including three major infestations in the 20th century (1970s, 1940s and 1910s) and possibly more localized outbreaks in the mid-1800s and mid-1700s. Evidence of larch sawfly outbreak is also strong, revealing three larger, regional outbreaks beginning in 1976, 1927 and 1891, and two smaller, more localized outbreaks beginning in 1954 and 1877. Evidence of very early outbreaks beginning in 1812, 1806, 1752 and 1732 is also observed. Reconstructions for both spruce budworm and larch sawfly revealed an insect regime that has closely paralleled that of the rest of the eastern boreal forest, particularly Quebec.

4.6 Climate change, fire and insects

Climate, fire and insect outbreak form a complex, interactive web, and natural disturbance dynamics in Labrador are sure to reflect a changing climate in the future. Boreal fire regimes have been and will continue to be greatly affected by changes in climate (Bergeron and Dansereau 1993, Flannigan et al. 1998, 2005; Amiro et al. 2001; Carcaillet et al. 2001; Bergeron et al. 2004), which in turn will induce changes upon the boreal landscape and stand structure (Brassard and Chen 2006; Carcaillet et al. 2001). Insect infestation, too, is influenced by climate (Greenbank 1956; Volney and Fleming 2000; Gray 2008), though the precise nature of these relationships is not fully understood (Gray 2008). There is an important need for future study of the link between climate and insect outbreak in Labrador.

Fire and insect regimes also interact. Changes to the fire cycle, for example, such as an apparent lengthening in certain parts of the eastern boreal forest (Bergeron et al. 2001; Lesieur et al. 2002), elevates the role of insect outbreak to greater significance (De Grandpre et al. 2000). In the absence of fire, spruce budworm outbreak can interrupt the natural progression toward conifer dominance by promoting mixed composition (Bergeron and Dansereau 1993; Brassard and Chen 2006; Kneeshaw and Bergeron 1999). Additionally, such outbreaks encourage the release of the understory by creating gaps in the canopy (Brassard and Chen 2006; Kneeshaw and Bergeron 1998), and can also result in an increased stand vulnerability to windthrow by way of defoliation (Brassard and Chen 2006; Morin 1994). Subsequently, windthrow can contribute significantly to the development of a multi-layered canopy, especially in older stands (De Grandpre et al. 2000). It is also responsible for the accumulation of coarse woody debris (CWD) – an important contributor to forest productivity (Brassard and Chen 2006) and vulnerability to fire as fuel build-up (Carcaillet et al. 2001).

Of course, the climate-induced changes to Labrador's natural disturbance regimes will depend entirely upon the type, degree and spatial distribution of the climatic change itself. The exact nature of the climate change likely to occur in Labrador is unknown, however, and this in turn presents a variety of scenarios regarding possible changes to Labrador's fire and insect regimes. The extent to which both of these dynamics are affected by a changing climate will ultimately dictate which regime will be more dramatically modified and, in turn, exert greater influence over the landscape in the future.

Observations from the past and forecasts of what may come offer a glimpse of what the future may hold for Labrador's ecology and landscape. Records of climate change in Labrador have revealed significant differences in coastal and inland regions. Coastal Labrador appears to have experienced an overall cooling tendency, while western Labrador has moved towards a more "continental" climate, with warmer summers and cooler winters (McKenzie and Dollin 2002). Data from central Labrador has revealed an increase in growing season temperatures since the late 1990s (Jacobs et al. 2005). Forecasts for Labrador suggest winter warming of 4 - 10°C and summer warming of 3 - 5°C by 2090 (Jacobs et al. 2005). The Canadian Regional Climate Model (Version 3.6.1) forecasts a 2.5 - 4.0°C change in Labrador's average winter (DJF) temperature by 2041-2060, relative to 1971-1990, with northern regions experiencing perhaps as much as a 7°C increase (Plummer et al. 2006). Average summer (JJA) temperature in Labrador for the same time period is predicted to increase by 2.0 - 3.0°C, with some northern areas warming by perhaps as much as 3.5°C (Plummer et al. 2006). Winter precipitation is projected to change very little through much of Labrador by 2041-2060, with 5% to 10% increases expected to occur only at the northern, western and southeastern tips of the territory. Summer precipitation is expected to increase between 5% and 20% throughout Labrador, with northern and central regions projected to experience the greatest increase (Plummer et al. 2006). This tendency toward warmer winters and wetter summers will have a significant impact upon the evolution of Labrador's natural disturbance regimes.

As elsewhere, Labrador's fire regime has been influenced and will continue to be influenced by this climate change. Over the past century and, in particular, within recent decades, fire frequency and burned area appear to have increased with the change in climate within the broader Canadian boreal forest (Weber and Flannigan 1997; Gillett and Weaver 2004). In the eastern boreal forest, however, a decrease in fire frequency has been observed (Bergeron et al. 2001). Predicted warming accompanied by increased precipitation would result in stands less conducive to fire activity (Flannigan et al. 1998; Carcaillet et al. 2001) and a subsequently longer fire cycle (Brassard and Chen 2006; Bergeron and Flannigan 1995). A continued lengthening of the fire cycle would be sure to have a significant impact upon the landscape, particularly with regard to post-fire regeneration (Zhang and Chen 2007). An increase in precipitation combined with a reduced fire frequency will likely exacerbate the challenge of paludification-prone forest floors in Labrador, which would result in a continued decline in the soil productivity (Simard et al. 2007).

Labrador's insect regime is also likely to be altered by climate change. Climate change will influence both the frequency and intensity of insect outbreaks (Volney and Fleming 2000). There is a lengthy history of spruce budworm and larch sawfly in western Labrador (see Chapter Three), and future occurrences of outbreak in Labrador could be devastating. If predictions of a lengthened eastern boreal fire cycle prove true, both balsam fir and white spruce – preferred budworm food sources – are likely to take on more dominant roles in Labrador's forests. Increasing time-since-fire precipitates movement from cyclic succession toward directional succession, wherein shade-intolerant species are replaced by shade-tolerant species (Brassard and Chen 2006; Bergeron et al. 2001; Lesieur et al. 2002). Proliferation of balsam fir could lead to fewer, large scale outbreaks resulting in high mortality rather than more frequent outbreaks with lower mortality rates (Bouchard et al. 2006). This is supported by Gray (2008), who predicts that under the Coupled Global Climate Model (CGCM3) B-1 scenario (whereby CO₂ levels are stabilized at 550ppm) the average increase in the duration of

spruce budworm outbreaks is approximately six years, with an average increase in outbreak severity of 15%. Regions most likely to experience the largest increase in outbreak duration included eastern Quebec (Gray 2008) and, presumably, western Labrador. Such an increase in duration would, on its own, result in far greater mortality, but in conjunction with the increased dominance of hosts balsam fir and white spruce resulting from a lengthened fire cycle, it could have enormous consequences (Bergeron and Leduc 1998).

Bouchard and Pothier (2008) suggest that increased occurrence of spruce budworm outbreak is not as closely linked to a lengthening fire cycle (and subsequent expansion of balsam fir) as might be assumed. This possibility could be further complicated by climate-induced changes to the timing of either spring emergence of spruce budworm or shoot development in host species. The establishment of feeding sites for spruce budworm are highly dependent upon the precise synchronization of the spring emergence of larvae with the development of host buds (Volney and Fleming 2000). While asynchrony characterized by early emergence can be tolerated, late emergence relative to shoot development appears less forgiving to the survival of budworm populations (Trier and Mattson 1997; Lawrence et al. 1997). Should a warming climate result in an earlier spring thaw with earlier coniferous bud development, populations such as budworm may not be able to adapt. Were such a change to occur, it is a possibility that balsam fir and white spruce could eventually “out-develop” the emergence of larvae, and that black spruce, currently a tertiary food source for spruce budworm due to its later shoot development, could become a preferred food source for budworm.

Climate change will also cause natural disturbance regimes in Labrador to interact with each other, leading to changes in stand characteristics. If fire frequency decreases, other disturbances such as insect and windthrow will gain greater importance in determining stand structure (Brassard and Chen 2006, Bergeron and Leduc 1998; Bergeron et al. 2001). Insect outbreak and windthrow contribute to the accumulation of coarse woody debris and a higher fuel load (Carcaillet et al. 2001),

potentially creating conditions for less frequent yet more severe fires. Climatic warming and a longer fire cycle would also increase the possibility of dramatic reduction in deciduous stands (Bergeron and Dansereau 1993) and would also have important consequences for species-dominance in the climatically-sensitive bog environment (Foster 1984b). Large-scale climate change, then, will have a significant impact upon the forest landscape through its influence upon both fire and insect disturbance. Indeed, a fire regime changed by climate warming may have a greater ecological impact than the climatic effects themselves (Weber and Flannigan 1997). Naturally, these evolving regimes will have a sizeable impact upon stand structure (Brassard and Chen 2006) and, ultimately, species distribution across all of Labrador.

The particular changes to species distribution caused by climate change are not easily predictable (Brassard and Chen 2006). Climate models have predicted that warming will be more intense in more northern, high latitude regions (IPCC 2007). Labrador may see an expansion of certain species as climate warming occurs, at least in areas not constrained by natural physical barriers inland (Payette 2007). Changes will be reflected at the climatically-sensitive forest-tundra, which may experience progressive tundra-to-forest shifts promoted by a warming climate (Payette et al. 2001). In northern Quebec, there has been some indication of a northward colonization of black spruce into the subarctic forest-tundra, as well as increased height growth of established stunted spruce as a result of 20th century climate change (Gamache and Payette 2005). It is highly doubtful that northward expansion in Labrador would remain in step with rapidly changing climate, however. Impediments to establishment such as wind exposure appear to delay growth response of trees in the forest-tundra (Gamache and Payette 2004). And while recent climate warming has resulted in some increased growth, it has yet to enable black spruce to improve the viability of its seed production such that an upward movement in the elevational treeline, for example, is imminent (Asselin and Payette 2006; Gamache and Payette 2004).

The future of the two jack pine stands at Redfir Lake-Kapitagas Channel is uncertain. Current conditions in southwestern Labrador – including its sandy, podzolic soils – seem ideal for jack pine growth and are conducive to further expansion (Parks and Natural Areas Division 1999). Brassard and Chen (2006), however, point out that post-fire abundance of jack pine relies heavily upon its pre-fire abundance which, in the context of a lower fire frequency, could result in its extirpation by way of succession (Bergeron and Dansereau 1993). Minor components of black spruce are present in the area (Parks and Natural Areas Division 1999), and in the absence of fire they could begin to dominate the small jack pine stands (De Grandpre et al. 2000) and result in the eventual disappearance of the remaining jack pine in this region.

4.7 Climate change and continentality

A discussion surrounding the future of Labrador's forests in the face of climate change would be incomplete without addressing the importance of continentality as an influence upon its natural disturbances. The demarcation of such a gradient offers a timely opportunity to speculate about the spatial distribution of climate-induced changes to forest dynamics. While such a gradient may previously have been assumed to exist, verification of its presence is an important step toward predicting spatial changes in the growth-climate relationship.

In the context of a warming climate, the theoretical line delineating “continental Labrador” from “maritime Labrador” is likely to shift. Summer temperatures will increase in Labrador, and so its dendroclimatology will shift too. As discussed in Chapter Two, peak summer temperatures in July proved to be ideal for tree growth at eastern, maritime-influenced sites, but to exceed the temperature optimum for trees at western, continentally-influenced sites. An increase in summer temperature at all sites will result in the northeastward movement of continental influences in Labrador as July temperatures begin to exceed more thresholds for optimum growth. It is possible that a warming growing season such as this could result in the evolution of a bi-modal growing season, where peak

temperatures result in stalled mid-season growth across western and central Labrador before reverting to a more unimodal distribution towards the closer proximity to the cold ocean currents of the Labrador Sea (Figure 4.2).

Shifting influences of continentality will likely play an important role in the geography of fire activity. Regarding the fire regime, it has already been noted how changes to temperature and precipitation patterns could impact the fire cycle in Labrador. Previous studies have predicted that the decrease in fire frequency that has occurred in the eastern boreal forest since 1850 will indeed continue as the climate continues to warm. Should the fire cycle indeed act as a function of climate, it is reasonable to assume that a west-to-east gradient of fire frequency is present in Labrador. Further study will be required in order to gain a better understanding of the nature and spatial distribution of fire cycles in various parts of Labrador, as we look to confirm whether the fire cycle does in fact decrease as one moves eastward.

Insect disturbance regimes will also be affected by the processes of continentality. Based on their study of the impacts of sawfly defoliation upon larch on the Quebec-Labrador peninsula, Filion and Cournoyer (1995) suggest that continental sites are more susceptible to outbreak. This would lead us to assume that gradient of insect activity is also present in Labrador (Figure 4.3). Though such a gradient was not apparent in the limited scope of the study in western Labrador, further comparative studies in eastern and northern Labrador could reveal its presence if a larger gradient was examined. And once again, shifting influences of continentality resulting from climate change could see a change in the nature and spatial distribution of insect activity in Labrador. Presumably, further studies will reveal an increase in insect activity in eastern parts of Labrador as the climate continues to be altered.

4.8 Conclusion

The forces of continentality currently influencing Labrador's dendroclimatology and natural disturbance regimes will continue to have an impact as the climate changes. Changes to Labrador's

fire and insect regimes will reflect the eastward-shifting of continental influences. It is anticipated that, as both summer temperature and precipitation in Labrador increase, fire frequency will decrease and insect activity will increase. Further study is required to gain understanding as the nature and spatial variation of fire and insect activity across regions of Labrador. Given that climate-induced changes to Labrador's disturbance regime will be extensive and complex (Weber and Flannigan 1997), prompt, thoughtful and creative deliberation will be required of forest managers and policy makers in Labrador. Changes to Labrador's forest management policies should reflect the particular changes occurring in its forests. Forest dynamics vary greatly not only on a national scale but also at a regional level, management practices should be tailored to the specific nature of the particular forests in question (Baskerville 1986; Bouchard et al. 2007). And while it is useful to consider past trends and effects of climatic change over the past century, it is also important to note that recent climate warming and subsequent changes to the boreal forest have occurred more quickly than earlier predictions have supposed (Soja et al. 2007). Current scenarios for the coming century predict rates of climatic change for which there is no precedent (Weber and Flannigan 1997), which suggests also the prospect of a disturbance regime and boreal forest dynamics that are foreign to the imagination, especially in Labrador.

4.9 References

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Figure Captions

- Figure 4.1 Convergence of continental and maritime influences. Western Labrador appears to be situated at the junction between the two climatic forces.
- Figure 4.2 Hypothetical future changes to summer temperature-growth correlations. Under warmer conditions, peak July temperatures at more moderate, coastal sites retain high growth-climate correlations. Peak July temperatures at inland, continentally-influenced sites exceed the threshold of optimum temperature, resulting in decrease growth-climate correlations during that month.
- Figure 4.3 Known and hypothetical continentality-induced expansion of insect activity. As continental sites are considered to be more susceptible to insect outbreak, climate warming in Labrador could see an eastward expansion of insect activity. Solid lines indicate insect activity, while dashed lines indicate the potential eastward expansion of insect activity hypothesized here.

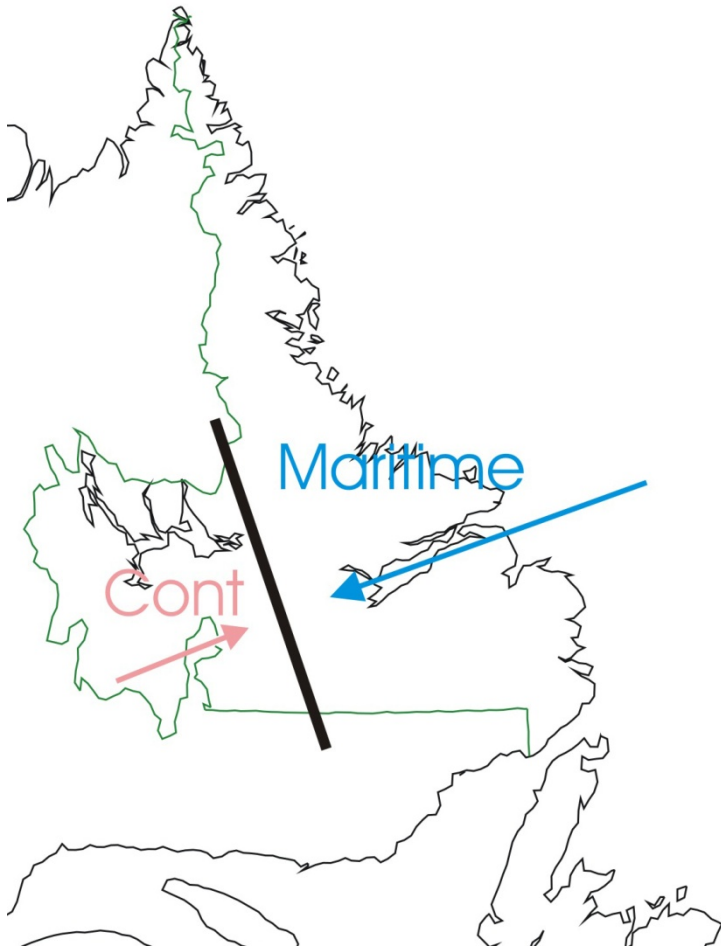


Figure 4.1

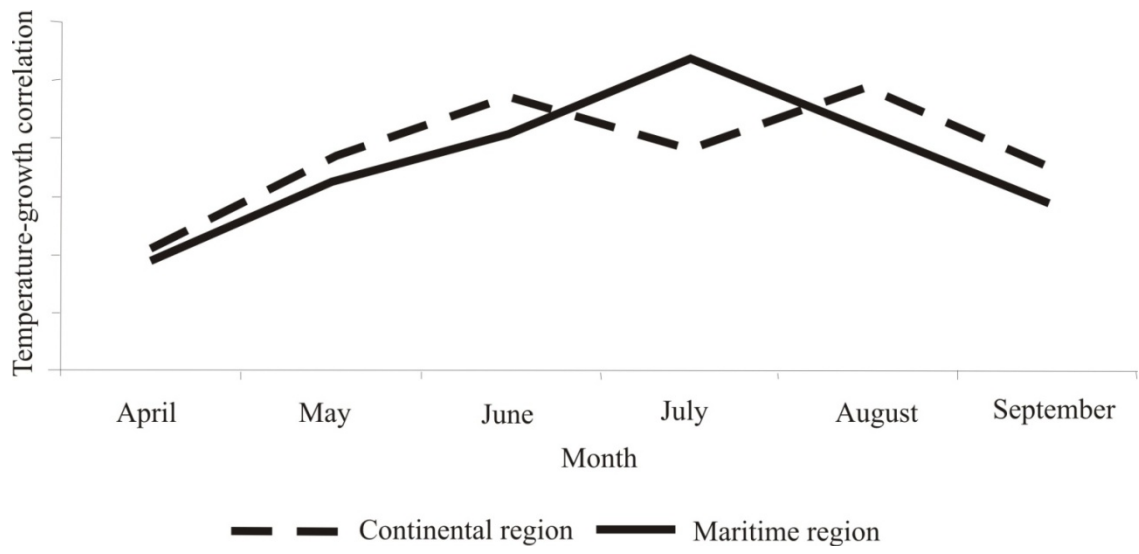


Figure 4.2

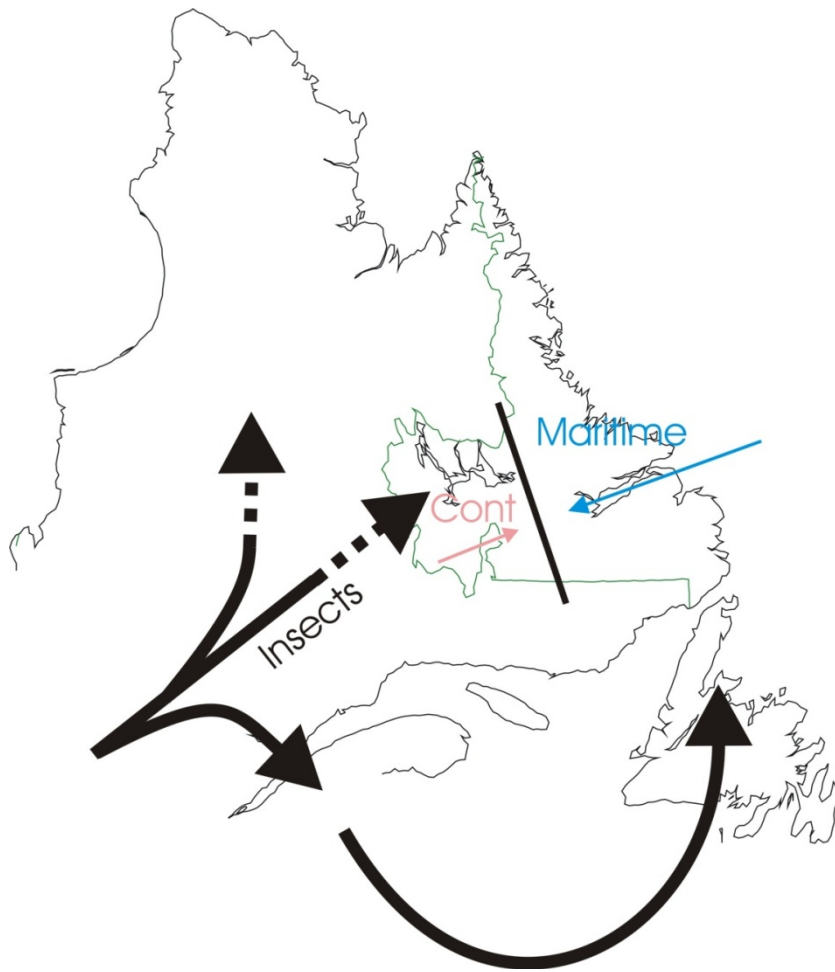


Figure 4.3

Chapter 5

Conclusion

Tree-ring evidence has provided valuable insight into past, present and, potentially, future forest dynamics in western Labrador. The imminence of dramatic climatic change has precipitated investigation into how various regions and communities will be impacted. As a largely under-developed and under-studied boreal region, western Labrador has been disadvantaged by a large gap in understanding of past and present forest ecology, let alone that of the future. The results presented here aid in addressing this gap in knowledge, and further help to predict potential future consequences that climate change may bring to Labrador.

Response function analysis for conifers in western Labrador reveals a dynamic growth-climate relationship. Radial growth has been found to correlate positively with summer temperature in this region, in keeping with results of studies in adjacent regions. Variations in the level of summer temperature-growth correlation are apparent, however, differing between western and eastern sampling sites. Maximum correlation values, signifying optimum temperature-related growth conditions are associated primarily with July temperature at eastern sites. At western sites, however, maximum growth correlations appear to “straddle” the month of July, when temperatures values reach their annual peak. Growth correlations from central sites are mixed, and seem to form a middle ground between peripheral sites to the west and east. This shift in growth correlations suggests that trees sampled at eastern sites in the sampling grid enjoy optimum growth conditions when temperatures reach their peak. At western sites, meanwhile, where peak July temperatures are higher, conditions appear to exceed the threshold for optimum growth and correlations decrease. I conclude that the results of this growth-climate analysis provide evidence of the convergence of continental and maritime influences in western Labrador, whereby a gradient of continentality is visible in the data. Such evidence leads to a more complete understanding of where this junction of converging climatic

forces is to be found, and provides a valuable clue as to the possible effects that a changing climate could bring to forest dynamics in Labrador.

Radial growth analysis of conifers in western Labrador has also revealed evidence of a long history of recurring insect activity in the region. The presence of such activity has been well-documented in nearby regions of the eastern boreal forest, leading to the supposition that similar processes have impacted Labrador as well. Results from the dendroecological analysis presented here confirm the supposition that bioclimatic and natural disturbance dynamics affecting adjacent areas are indeed present in Labrador. Furthermore, this analysis has provided insight into the temporal and spatial similarities between Labrador and other eastern boreal regions. Through tree-ring analysis, precise dating of insect outbreak could be obtained and compared between sites for synchronicity. These dates could then be further evaluated for synchronicity through comparison with previous historical reconstructions. The identification of insect outbreaks for both larch sawfly and spruce budworm has also revealed spatial trends across the sampling grid, whereby smaller, more localized outbreaks can be differentiated from larger, more regional outbreaks. Once again, these results were then compared with those of previous studies as a further means of measuring outbreak magnitude.

Particularly evident as a benefit to the dendroclimatological and dendroecological analysis presented here is the use of a systematic sampling grid. Dendroclimatological analysis, in particular, has typically made use of targeted sampling sites at climatic extremes, where the limiting effect of climate upon tree growth is more easily observed. Sacrificed by this traditional method, however, is the ability to measure or observe changes in the growth-climate relationship across spatial gradients. The power of the sampling design employed here is evident in the revelation of results in both continentality and outbreak magnitude in a single regional study.

The nature and location of the convergence of continental and maritime influences in Labrador is sure to change in the context of a warming climate. As warming occurs, the bioclimatic interactions

that characterize western, continentally-influenced areas of Labrador, will likely begin to move eastward. Warmer winters coupled by warmer, wetter summers will result in a lengthening fire cycle in Labrador and, subsequently, a more influential presence of insect activity. Insect activity, such as larch sawfly and spruce budworm, is likely to increase in frequency in eastern, maritime-influenced regions of Labrador.

Despite the benefits of the research presented here, much study of forest dynamics, bioclimatic interactions and gradients of change is still needed in Labrador. In particular, future study in the coastal and northern regions of Labrador would provide useful opportunities for comparative study and, in the context of a rapidly changing climate, are all the more urgently required.

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