DENDROCLIMATOLOGY OF *Picea glauca* AT TREE LINE IN NORTHERN LABRADOR, CANADA

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Dendroclimatology of *Picea glauca* at tree line

in northern Labrador, Canada

by

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Abstract

This thesis applies standard dendroclimatological techniques to compare the radial growth response of the dominant species persisting across treeline in northern Labrador, Canada. White spruce (*Picea glauca* (Moench) Voss) tree-ring width chronologies were constructed from ten sites spanning treeline in northern Labrador from the Labrador Sea to the Québec border. The effects of climate on radial tree growth were examined at various spatial and temporal scales.

This is the first study to conduct a regional dendroclimatological analysis of Labrador's treeline with respect to delineating the extent of maritime and continental climatic influences on radial growth. Pearson product moment correlations and response function analyses were used to identify two distinct tree bioclimate zones acting on treeline in northern Labrador. The arctic-maritime zone consists of the northern extension of treeline along Labrador's coast and is primarily characterized by a strong positive correlation to June and July temperatures of the current growing season. Also defined is the subarctic maritime zone encompassing the area immediately below the arctic maritime zone. Trees here also demonstrate a strong positive sensitivity to June and July temperatures, as well as a negative association to current spring temperatures and a positive correlation to previous fall temperatures. These findings indicate that a bioclimatic shifting of the climate-radial growth relationship of white spruce occurs at roughly 56°75'N along treeline in northern Labrador. Furthermore, as white spruce trees at their northern range limit are expected to be susceptible to future changes in climate, radial growth models using only climate variables are produced and future forecasts (2009 - 2100) are also developed. Models were constructed using a stepwise regression analysis, employing monthly compiled variables for all ten sites. Model outputs were cross-referenced and important climate variables to white spruce radial growth were verified and landscape patterns of climatic responses were noted. Radial-growth forecast model outputs illustrate a generally decreasing radial growth rate at extreme northern locales, and moderate radial growth increases for more southern sites by 2100 AD. The radial growth forecasts produced here suggest that southern and intermediate latitude treeline sites may expand inland, while no expansion is expected at extreme northern locales along the coast.

Keywords:

Dendroclimatology, northern Labrador, tree line, white spruce, *Picea glauca,* radial-growth forecasting, climate change.

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Chapter One

1. Introduction and Overview

The landscape in northern Labrador, Canada, is topographically complex. The eastern coast is dissected by bays and fiords that rise abruptly to the west to an inland plateau that ranges from 200 to 500 m above sea level (asl) and is dotted with low-lying lakes and ponds. The region's vegetation assemblage is that of a subarctic forest-tundra transition zone (Payette et al. 2001). Tree populations persisting here are primarily in the form of 'tree islands' confined to lowland seepage sites, whereas upland, well-drained sites are inhabited by tundra vegetation (Payette et al. 2001). These 'tree islands' represent the easternmost extension of boreal forest tree line in Canada. This thesis focuses on the radial growth response of the dominant tree line species in Labrador – white spruce (*Picea glauca* (Moench) Voss) – to local climate.

Tree-ring studies using white spruce in northern Labrador have shown that measurable relationships exist between radial growth and climate; however, most of this research is comprised of single-site studies that lack a regional perspective (e.g. D'Arrigo et al. 1993, 1996, 2003). Labrador's diverse landscape and topography, combined with the proximity of the cool Labrador Sea results in high spatial climate variability (Banfield 1993). As such, tree line sites need to be sampled across northern Labrador from the Québec-Labrador border in the west, to the coast in the east, so as to capture all local climate zones. Standard dendroclimatology techniques are used to investigate the climate sensitivity of white spruce trees growing at Labrador's tree line and to identify spatial patterns in this climate sensitivity. Future white spruce growth at tree line may also be forecast using future climate scenarios under conservative and moderate estimates of atmospheric carbon dioxide forcings to test whether these sensitivities may change in the future.

1.1. Tree lines

Tree line ecosystems consist of tree species persisting at the edge of their ecological limit and thus are especially sensitive to changes in climatic trends. Globally, studies have shown a largely positive response between warmer temperatures and the radial growth of trees at the edge of their range (Lamb 1985, Lloyd and Fastie 2003, Esper and Schweingruber 2004). This is consistent with current ecological models which predict that warming will induce northern and upslope migration of tree line (Soja et al. 2007). However, at a few locations, trees at their limit of growth have responded negatively to warming temperatures (Kullman 1987). Other aspects such as moisture and disturbance events can also effect radial growth (Grace et al. 2002), but they are not as consistent an overriding factor as temperature, instead relying on localized site effects.

For instance, trees have been shown to be sensitive to winter snowfall (Gamache and Payette 2004) and to spring/summer precipitation (Wilmking et al. 2004; D'Arrigo et al. 2003); the latter resulting from drought stress or moisture saturation during the growing season, both of which restrict radial growth (Wilmking et al. 2004; D'Arrigo et al. 2003). In Alaska, white spruce trees growing at tree line sites have experienced temperature-related drought stress during summer months, resulting in a negative relationship to warming temperatures (Jacoby and D'Arrigo 1995; Barber et al. 2000; Wilmking et al. 2004). Although a comparable response has yet to be observed in eastern North America, it has been suggested that this type of relationship to tree growth stress may be forthcoming due to the higher than normal temperatures expected in the future (Payette 2007).

1.2. White Spruce (*Picea glauca* (Moench) Voss)

White spruce is widely distributed transcontinentally throughout the boreal forest of Canada and into the United States in the Great Lakes region. It is a very robust species capable of tolerating cold-coastal and cold semi-arid climates, with temperatures ranging from -50°C in the winter up to 30°C in the summer (Schweingruber 1993). At tree line, white spruce commonly forms disparate 'tree islands' beyond the latitudinal and altitudinal limit of other competing species, whereas nearer to the continuous tree limit it coexists with black spruce and eastern larch (Payette 1993).White spruce is a shallow rooting species of conifer which makes it ideally suited for northern Labrador's permafrost terrain (Barbour and Billings 2000). White spruce in northern Labrador routinely reaches an average height of approximately 10 m and a stem diameter ranging from 40 to 80 cm. In northern regions, where trees have escaped forestry, they commonly reach ages of 200 years or more, making them suitable for dendrochronological study. On the other hand, mixed stands of white spruce and balsam fir can be decimated by outbreaks of spruce budworm (*Choristoneura fumiferana*) and fire disturbance (Arsenault and Payette 1992; Lavoie and Sirois 1998; Drever et al. 2006), limiting stand age (Schweingruber 1993; Nealis and Regniere 2004).

1.3. Climate

The climate of Labrador is spatially varied due to arctic, continental and maritime influences. The climate across northern Labrador is classified as subarctic, having relatively short summers with long daylight hours and cool temperatures. In coastal regions, however, winters are milder and summers cooler compared to inland locales. For example, climate normals for coastal Nain are 6.2°C and 10.7°C in June and July, respectively, and -18.5°C and -18.7°C for January and February, respectively (NCDIA 2010). This compares to the inland Schefferville climate normals of 8.5°C and 12.4°C in June and July, respectively, and -24.1°C and -22.6°C in January and February, respectively (NCDIA 2010) . This dramatic maritime effect is caused by the confluence of synoptic-scale systems that originate over the North Atlantic and the North American continent. From the northeast, the Labrador Current carries cold, polar water southward into the Labrador Sea, resulting in moderated air temperatures and increased atmospheric moisture along the coast. In the west, prevailing westerlies carry relatively warm, dry air from the mid-latitudes over Labrador during the summer season (Banfield 1993). The distribution of ecoregions across Labrador mimics this climatic pattern suggesting a close relationship between climate and vegetation (Meades 1989).

During the spring, cold water in the adjacent Labrador Sea combines with offshore winds to produce foggy conditions along the coast, resulting in approximately 70 less hours of sunlight than farther inland. By July, however, conditions are nearly identical with both coastal and inland locales receiving over 190 hours of sunlight each (Banfield 1993). In the fall, the first frost is roughly synchronous across northern Labrador. Annual precipitation ranges from 600 to 800 mm, but may exceed 1000 mm in coastal areas, with over half falling as snow during the winter months.

1.4. Dendrochronology

Dendrochronology – the study of tree rings – has provided significant knowledge and insight into which climatic and non-climatic factors can control a tree's growth. A tree's annual radial growth commences when air temperatures warm using energy stored during the previous year's growth to break the winter dormancy. The first radial-growth cells formed – called earlywood cells – have thinner cell walls and are lighter in appearance. Cells formed at the end of the radial-growth season – called latewood cells – have thicker cell walls and a darker appearance. These latewood cells delineate a sharp transition with earlywood cells, resulting in a visible annual ring that demarks a year of radial growth (Fritts 1976). Both tree-ring width and wood density measurements have been shown to capture a climate signal from the year of formation. Ring-width is generally thought to be more sensitive to summer temperature conditions, whereas ring-density variations are considered to better reflect extended warm season temperatures (D'Arrigo et al. 2002). For example, in a study encompassing the entire extra-tropical northern hemisphere, Briffa et al. (2002) showed that tree-ring density series are sensitive to air temperatures from April to September, whereas tree-ring width series are more sensitive to June–August temperatures (Briffa et al. 2002).

Annually-resolved tree ring records can be accurately dated using crossdating techniques to provide high-frequency environmental proxy data. This process is based on the fact that all trees, in particular those of the same species, growing in the same location, must experience very similar environmental conditions and so will have similar radial growth patterns (Fritts 1976). Crossdating is a process whereby the tree-ring pattern between all samples from a location is matched in order to assess the data quality and to anchor the tree-ring pattern in absolute time. The resulting dated tree-ring chronology is referred to as the master chronology. The crossdating process can also be used to extend the length of the tree ring chronology by matching the ring width pattern of an undated sample to the master chronology. This process can be repeated indefinitely and has resulted in millennia-long chronologies (Fritts 1976; Luckman and Wilson 2005).

Once a tree ring chronology is accurately crossdated, it is standardized to produce a unitless index of radial growth. This process is necessary because there are a variety of factors – biological, age-related, ecological and climatic – which together produce an annual ring (Fritts 1976). The standardization process removes unwanted, age-related trends in radial growth by fitting a theoretical curve to a time series and subtracting or dividing it by an idealized curve. For example, the most common standardization method is a negative exponential curve which removes the age-related radial growth of a tree, since younger trees usually produce wider rings due to their smaller circumference and so their radial-growth pattern mimics a negative exponential trend. This so-called rigid detrending only removes low-frequency patterns, such as age, from the data. There are several detrending options, however, some of which remove various amounts of high and low frequency data, depending on the focus of the research (Helama et al. 2004).

1.5. Dendroclimatology

Dendroclimatology relates the radial-growth trends of trees to climate. This application is based on the fact that the radial growth of trees living at the edge of their range is generally limited by a single climate factor; thus a slight change in this factor will produce a measurable change in the ring characteristics for that year (Fritts 1976). Using the relationship between a series of tree's radial growth and instrumental climate records, both annually-resolved climate reconstructions for several centuries predating the local instrumental climate records are attainable, as well as future forecasted tree growth under different climate scenarios.

Dendroclimatic reconstructions are an important tool in determining past climatic variability at local, regional and hemispheric scales. Alternatively, forecasting future tree success or failure under changing future climatic conditions can provide valuable information for both the forest industry and forest conservation.

1.6. Thesis Focus

This thesis focuses on the direct relationship between radial-tree growth and climate in order to determine which environmental conditions exert the greatest influence on white spruce growth across tree line in northern Labrador. The tree line of northern Labrador has a configuration with both north-south and east-west elements and dendroclimatological analysis will be used to understand the major climatic controls influencing this spatial pattern. These relationships are then used to forecast white spruce radial growth to the year 2100 using climate scenarios generated from general circulation models. Together this analysis allows for a long-term assessment of how radial growth at tree line in Labrador has functioned in response to past climate and how it may respond to projected future climate.

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Co-authorship Statement

The design and development of the research proposal were completed by me, with input from Colin Laroque and Trevor Bell;

The practical aspects of the research were completed by me, with logistical support by Colin Laroque, Trevor Bell, Ben Phillips, Mariana Trindade and Amanda Young;

All data analysis was completed by myself;

All manuscript preparation was completed by me with comments and editorial suggestions from Colin Laroque and Trevor Bell.

Chapter 2, "Spatial heterogeneity in radial growth-climate relationships across tree line in northern Labrador" has been submitted for publication.

Chapter 2

2. Spatial heterogeneity in radial growth-climate relationships across tree line in northern Labrador

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2.1. Abstract

Northern Labrador is highly varied both topographically and climatically. From the east, strong climatic mechanisms related to the adjacent Labrador Sea create a powerful maritime influence on Labrador's regional climate. Topographically, an inland tundra plateau inhabited by scrub vegetation is dissected by deep-cutting fiords and rivers from the east, creating sharp elevational contrasts. At the margins of these lower-lying water bodies arboreal growth survives, delineating Labrador's latitudinal tree line. This study uses dendroclimatological analysis to observe the extent of maritime and continental influences on the radial growth of white spruce (*Picea glauca* (Moench) Voss), the dominant tree species in Labrador's north. Ten sample sites were selected spanning the extent of the tree line from its northernmost position along the coast to the Québec-Labrador border in the south-west. Pearson product moment correlations and response function analyses were utilized to identify two distinct tree bioclimate zones within the study area. The arctic-maritime zone is comprised of the northern extension of tree growth along Labrador's coast and is predominantly characterized by a strong sensitivity to June and July temperatures of the current growing season. Also defined is a subarctic maritime zone encompassing the area immediately below the arctic maritime zone. Trees growing within this zone also illustrate a strong sensitivity to June and July temperatures, in addition to current spring temperatures and previous fall temperatures. These results demonstrate that a bioclimatic shifting of the climate-radial growth relationship occurs at approximately 56°75'N, roughly the same latitude as northern Labrador's most populous town, Nain.

Keywords:

Dendroclimatology, northern Labrador, tree line, white spruce, *Picea glauca,* Labrador Sea.

2.2. Introduction

Northern tree line ecosystems are traditionally limited by a latitudinally defined temperature gradient (Larsen 1980; Arno and Hammerly 1984; Briffa et al. 1994; Payette et al. 2001). These latitudinal tree lines generally form a smooth south-to-north transition from continuous forest gradually receding to tundra vegetation. Northern tree line ecosystems have been shown to be sensitive to shifts in climatic conditions (Esper and Schweingruber 2004; Gamache and Payette 2004) and the most recent changes in the dynamics of northern tree lines have been attributed to increased warmth in the late 19th century (Payette 2007). The vast majority of northern tree lines worldwide have responded positively to the recent warming by advancing northward into the tundra (Lamb 1985; Lloyd and Fastie 2003; Esper and Schweingruber 2004), while relatively few sites have exhibited a receding tree line (Kullman 1987).

It is in northern regions where the most drastic changes in climate have been noted and are expected to continue (Raisanen 2001; Hassol 2004; Johannessen et al. 2004; Chapin et al. 2005; Trenberth et al. 2007). Recently, Payette (2007) has described the northern Québec-Labrador tree line as the most climatically stressed tree ecosystem in eastern North America. Adding to this, the northern Labrador tree line is unusual in its own right in that it appears to exhibit both advancement and retreat of tree line position over short distances. Payette (2007) documented that sites along Labrador's coast have experienced expansion in recent decades, whereas inland sites have displayed a slow forest regression over the last century. Additionally, tree line sites along Labrador's coast are able to persist at higher latitudes than their inland counterparts (Figure 2.1). These aspects of the tree line are noteworthy because they yield two regions of forest-tundra transition; a traditional north-south orientation and an irregular east-west orientation. Given the exceptional configuration of the northern tree line in Labrador, the climatic stress on radial growth and the different responses of coastal and inland sites, a regional approach to the dendroclimatology of the tree line seemed warranted.

Complex atmosphere, ocean and sea ice conditions combine to constitute a significant maritime influence on the climate of Labrador (Dickson et al. 1996; Banfield and Jacobs 1998; D'Arrigo 2003). The sparse climate stations and short climate records in Labrador, however, have limited research on the spatial influence of these controls on climatic patterns. Consequently, researchers have attempted to better understand Labrador's climatic variability through the use of tree-rings as a proxy source of past climatic conditions. Early studies (e.g. Cropper and Fritts 1981; D'Arrigo et al. 1992; Schweingruber et al. 1993; Briffa et al. 1994), however, were too localized in their design to reveal any regional climatic influences on a landscape-scale. Acknowledging this, newer studies (e.g., Payette 2007; Nishimura 2009; Dumaresq et al. 2010; Trindade et al. 2011) have incorporated a much larger-scale perspective in their sampling design, which has permitted a more regional representation of climatic influences on the forests.

For example, Nishimura (2009) demonstrated a shift in the climate-radial growth relationships of trees between central and western Labrador. By using a systematic, gridded sampling network, Nishimura (2009) was able to delineate a transition zone in forest-climate sensitivity at roughly 300-350 kilometres inland from the coast. This pattern in tree bioclimatic zones was attributed to spatial changes in the onset timing of optimal temperatures for radial growth across Labrador. To the west, about 330 km inland from the Labrador Sea coast, radial growth is driven by a continental climate characterized by strong positive correlations with May-June temperatures. To the east, radial growth responds to cooler, maritime temperatures transitioning from a reliance on primarily June-July temperatures to solely July temperatures, with proximity to the coast.

Dumaresq et al. (2010) built upon this research by illustrating that another transition zone existed in the eastern half of Labrador. By adopting the same methodological approach as Nishimura (2009), Dumaresq et al. (2010) illustrated that radial-tree growth at immediately coastal sites is subjected to a 'hyper-maritime' climatic influence. This effect – to be distinguished from a 'maritime' influence – is characterized by a more subdued response to July temperatures and elevated correlations with August-September temperatures, reflecting the delayed climatic influence of the adjacent moderating Labrador Sea. In both studies, precipitation did not limit radial growth in any of the four study species.

The main purpose of this study is to map spatial patterns in the radial growth-climate sensitivity of the dominant conifer species persisting across Labrador's tree line. It is important to determine if Labrador's unusual tree line configuration is the result of maritime or hyper-maritime climatic influences, as defined by Dumaresq et al. (2010), more traditional latitudinal influences as defined by the temperature signature of continental influences (Nishimura 2009), or possibly a confluence of both. By investigating the dendroclimatology of Labrador's tree line, this study seeks to better understand the spatial variability of climate across northern Labrador from a more regional perspective than previously attempted. Furthermore, it is anticipated that this work will highlight maritime influences on tree lines in other coastal regions, as this type of research is not well represented in circumpolar tree-ring records (Briffa et al. 1994; Overpeck et al. 1997; D'Arrigo et al. 1999; Mann et al. 1999), and the tree ecology of these zones of confluence of maritime and continental influences are poorly understood.

2.3. Study Area

Tree line sites were sampled at regular intervals across Labrador's tree line, extending from its southern position at the Québec-Labrador border to its northernmost position on the northeast coast of Labrador (Figure 2.1). All study sites fall into a region between 56 and 58°N and 62 and 64°W and are subject to increasing degrees of continuous permafrost with latitude and altitude. Here, forest stands typically exist in the form of insular tree islands confined to low-lying areas around or near a body of water, giving way to tundra vegetation at well-drained, upland sites (Payette et al. 2001). Inland elevations within the study region range from 200 to 500 m asl, whereas along Labrador's dissected coast, trees grow at or near sea level (Table 2.1). White spruce (*Picea glauca* (Moench) Voss) is the dominant tree species persisting at tree line sites in Labrador (Rowe 1972; D'Arrigo et al. 1992; Farrar 1995). This is particularly true along Labrador's northern coast, but shifts to co-dominant status with black spruce (*Picea mariana* (Mill. B.S.P.) and/or eastern larch (*Larix laricina* (DuRoi) K. Koch) at interior locales (Payette 2007).

2.4. Methods

At each sampling site core samples were taken from 20 trees using a 5.1mm increment boring tool. Sampling typically occurred on sites where trees were 100+ years old; however, not all samples are of this length. Tree line sites were also selected based on their accessibility via floatplane. Due to the difficulties in finding suitable sampling sites with 100+ year-old trees and near a large enough body of water to safely land on and take off from, other selection criteria such as slope, aspect, elevation, and substrate were commonly ignored. The resulting tree-ring data are therefore a product of an opportunistic sampling strategy. Although micro-site characteristics were largely disregarded, all sampled stands occurred in typical habitat for white spruce trees in this environment. At each sampling site two cores were extracted per sampled tree, totalling 40 cores per site, and 400 cores across the network. The collection of two cores per tree allowed for a direct comparison of both number and width of rings, thus minimizing the occurrence of ring anomalies, such as missing or false rings (LaMarche 1982). Cores were stored in straws for transport to the Mount Allison Dendrochronology Lab, where they were air-dried, glued into slotted mounting boards and sanded with progressively finer grades of sandpaper until individual ring resolution was clear. Annual ring-widths were analysed from the bark inward using a Velmex stage capable of measurements to the nearest 0.001mm.

Annual ring-width measurements were first visually and then statistically crossdated using COFECHA in order to assess homogeneity of signal within the ring patterns of each core (Holmes 1983; Grissino-Mayer, 2001). All ten tree line chronologies developed for this study were analyzed between trees to produce averaged individual site Pearson product-moment correlation coefficients or a mean series intercorrelation (MSI) – r-values based on overlapping 50-year segments. Pearson's r-value describes the strength of linear dependence between each core's growth and an overall master chronology; values over 0.328 are significant at the 99% confidence interval (Grissino-Mayer 2001). Also calculated in this analysis, is an average mean sensitivity (AMS) value for each chronology. The AMS value measures the high-frequency variation between annual rings by calculating average deviation from one year to the next. (Fritts 1976; Grissino-Mayer 2001). Values for AMS between 0.1 and 0.19 are considered low, between 0.2 and 0.29 moderate and greater than 0.3 high; AMS values are recognized to be a good measure of a tree's sensitivity to climate (Grissino-Mayer 2001). Measurements were then standardized using ARSTAN (Cook 1985) to remove the biological growth trend using a single negative exponential detrending spline. This procedure effectively eliminates age-related radial growth patterns so that ring-widths only reflect environmental constraints. Master chronologies for each site were constructed from the averages of each core at each sampling site using the robust mean function in ARSTAN (Cook 1985).

Mean monthly temperature and total monthly precipitation data were used as inputs to the response function analysis in the computer program DendroClim2002 (Biondi and Waikul 2004). DendroClim2002 uses bootstrapped correlations to assess the strength of radial growth-climate relationships in a given chronology. For this study, each master chronology was analyzed against a composite regional climate record (Table 2.2) for the period from April of the previous growth year (t-1) to October of the current growth year (t-0). From this analysis, correlation values for each month were obtained and assessed for statistical significance. These results were then evaluated for biogeographical patterns across sites and interpreted in the context of maritime influences, latitudinal influences or both.

2.4.1. Climate data

As documented by Vincent and Gullet (1999), the density and temporal extent of northern climate stations in Canada are severely limited relative to their southern counterparts. Northern Labrador is no exception; as a result previous studies have used longer, continuous records of historical climate from geographically distant climate stations for their analysis (D'Arrigo et al. 2003; Payette 2007). However, unlike these previous studies this study sought to create a composite regional climate record representative of the entire study area in northern Labrador by combining the continuous and discontinuous records of historical climate from a network of operational and non-operational climate stations within the region. Individual climate station data were obtained from Environment Canada for the purpose of establishing radial growth-climate relationships for northern Labrador. The bulk of the historical climate data comes from the Nain station whose record is long, but discontinuous. In order to fill in the missing data from the Nain station an order priority was given to nearby climate stations (i.e., Indian House Lake, then Border, then Hopedale, then Makkovik and finally Cartwright). This priority order was given based on station proximity to the sampling transect. In total, five climate stations were used for monthly mean temperature variables and six for monthly total precipitation variables to create a record of climate 69 years long (1940-2008) (Table 2.2). This was deemed acceptable because the sampling transect itself spans across the coastal lowlands to the inland plateau of northern Labrador, but also because no alternative authentic regional climate data exists for the region. Every effort was made to ensure that only data most representative of the study area was used. As such, nearly 97.3% of the climate data originates with the 4 stations that are either located within or just south of the sampling transect – Nain, Indian House Lake, Border and Hopedale. (Figure 2.1, Table 2.2). The two other stations –Makkovik and Cartwright – are located along the coast between 240 and 450 km from the most southern sites and account for the remaining 2.7% of the climate data (Figure 2.1, Table 2.2). When constructing the composite regional climate record, months of overlapping data were checked and a good agreement was found for Nain, Indian House, and Border, and Hopedale, but as one would expect, Makkovik and Cartwright contained more and more deviation from the Nain mean as each site was progressively farther from treeline. Monthly mean temperatures between coastal and inland stations were similar during overlapping growing seasons (+/-0.75 °C), however more extreme in the winter when trees are dormant (+/- 6 °C). Precipitation is more uniform across the region (GN&L 1996) with the other stations deviating at most 30 mm from the Nain site and here again most of the difference is found outside the growing season.

2.5. Results

The average time-span of the ten chronologies was 236.7 years, with an average tree core length of 122.5 years (Table 2.1). All site master chronologies exhibited highly significant mean series intercorrelations based on 50-year overlapping segments, above the threshold of 0.328 at the 99% confidence interval; with an average value of 0.599 (Grissino-Mayer 2001). The average mean sensitivity across the ten chronologies was 0.201 indicating that white spruce at tree line in Labrador are sensitive to year-to-year fluctuations in their environment (Grissino-Mayer 2001).

A correlation matrix using a common 110-year time frame of 1899 to 2008 revealed positive statistical relationships between all site chronologies (Table 2.3). The strength of the correlations ranges from an r-value of 0.361 to 0.841 for the 45 possible combinations, with an average value of 0.583. These results establish that very strong correlations exist between all sites, and all chronologies are highly significant with each other at the 0.0005 level. The most southern and south-western sites (i.e. sites 6-10) exhibited strikingly high, above-average correlations with each other, with nine of ten combinations above 0.610 (Table 2.3). Sites 4 and 5 displayed average correlations with sites to the north (e.g. sites 2-3) and south (e.g. sites 6-9), but exhibited below average correlations with sites 1 and 10, the northernmost and south-westernmost sites, respectively. The northern sites 2 and 3 shared a very strong correlation at 0.681, whereas site 1, representing the northern limit of trees in Labrador, correlated weakest with all other site locations.

Response function analysis using the composite regional climate record (1940-2008) generated the highest correlation values when radial growth was compared to current growing season temperatures (Table 2.4). The response functions of the ten chronologies to climatic parameters illustrates white spruce growth at tree line to be predominantly influenced by summer temperatures (June-July) of the current growing season (Table 2.4). Mean fall temperatures (Sept-Oct) of the previous growth season also demonstrated some control over radial growth across tree line. At northern sites (i.e. 1-5) previous fall temperatures negatively influenced growth, whereas at southern sites (i.e. 6-10) a positive correlation was linked to previous year warm fall months. Conversely, mean monthly spring temperatures (Apr-May) of the current growth season had a largely negative effect on radial growth across most sites (Table 2.4). A notable exception to these observations is found at site 8, which demonstrated a negative response to both current and previous fall temperatures, despite its southerly location.

Mean monthly precipitation of the current growth season or the preceding fall had few significant effects on radial growth at tree line; however, radial tree growth did respond overwhelmingly negatively to precipitation during the spring and summer of the current growth season (Apr-Aug) (Table 2.5).

2.6. Discussion

2.6.1. Correlation Analysis

The generally high inter-site correlation values between all sampled tree line sites suggest a relatively synchronous growth signal across Labrador's north. This synchronous growth signal is interpreted as the climatic result of the proximity of all ten sample sites to the Labrador Sea (Figure 2.1). However, one significant spatial pattern did emerge; southern sites tended to be more highly correlated with each other, which suggests that additional or a different combination of climatic factors may be affecting tree growth along this part of Labrador's tree line (Table 2.3). It is likely that site elevation differences combined with increasing distance from the coast for the southern tree line sites modifies their radial-growth response to a maritime climate regime.

2.6.2. Response Function Analysis

The results of the response function analysis helped elaborate on the correlation analysis; that trees at all tree line sites are responding to very similar maritime climatic controls. All sites responded positively to warm summer temperatures (June/July) during the current growing year, agreeing with previous studies conducted in the region (i.e., D'Arrigo et al. 2002; Payette 2007). Similarly, the significant negative correlations associated with springtime temperatures (Apr/May) were also previously documented for the region (D'Arrigo et al. 2002; Payette 2007). This analysis also indicated that more southerly sites were better able to respond to the warmer fall conditions generated by the adjacent Labrador Sea.

The results of our study suggest that two subtly different tree bioclimate zones exist across tree line in Labrador; here named the 'arctic maritime' zone and the 'subarctic maritime' zone. To ensure these zones were not the artefact of the composite regional climate record dominated by Nain, four long-term climate stations from further afield (i.e., Goose Bay, Cartwright, Hopedale, and Shefferville) were also analyzed individually using the same type of analysis, and the same pattern groupings emerged. The newly defined "arctic maritime" zone encompasses a region inclusive of sites 1-5, located at the extreme northern end of the tree line position in Labrador (Figure 2.1). This zone is broadly defined by both a latitudinal and maritime climatic influence. Within this zone radial growth is most linked to June and July temperatures of the current growing season as trees need to complete their growth cycle in an abbreviated growing season. Here, the moderating effect of the Labrador Sea on fall temperatures is less effective at this higher latitude; thus trees growing in this region are unable to take advantage of the extended growing season afforded to trees farther south.

The "subarctic maritime" zone consists of the southern and southeastern portion of tree line; sites 6 through 10 of the network. This zone is characterized by significant negative correlations with spring temperatures indicating considerable springtime moisture stress on trees growing there. Due to decreasing latitude, trees in this zone experience warmer, more abrupt spring temperatures. This likely results in desiccation damage to needles as air temperatures become sufficient for photosynthesis, but persistent frozen ground conditions restrict the ability of roots to supply adequate moisture. This phenomenon has been noted in previous research (Jacoby and Cook 1981; D'Arrigo et al. 1992; 2003). Although warmer spring conditions probably result in needle damage early in the growth year, it also causes an earlier melt of snow cover and thaw of the active layer, which in turn results in an earlier start to the white spruce growth cycle. Radial growth in this region is still most positively associated with June and July temperatures of the current year of growth; however, trees in this zone also illustrate increasingly positive relationships with both previous and current fall temperatures. This indicates that trees here are able to benefit from an elongated growing season, as well as being able to begin the storage of photosynthates for use in the following growing season during the warmer, maritime fall conditions (Jacoby and Ulan 1982).

Tree bioclimate zones, such as the ones described above, have been documented across Labradors' forests in both the south-eastern, central and the south-western regions of Labrador by Dumaresq et al. (2010) and Nishimura (2009), respectively. Much like the termed 'hyper-maritime' zone delineated by Dumaresq et al. (2010) along Labrador's southeastern coast, it would appear that the southern portion of Labrador's northern tree line is also dependent on late-summer and fall temperatures of the current growing year. Whereas, the northern section of coastal tree line appears to be acting much more like the 'maritime' condition co-delineated by Nishimura (2009) and Dumaresq et al. (2010) in central-eastern Labrador.

2.6.3. Tree line position

Payette (2007) reported that inland tree line sites have experienced poor rates of seedling establishment and radial growth over roughly the last 250 years, whereas sub-arctic, coastal sites have recorded an increase in seedling establishment and radial growth throughout the 20th century. This contrast was attributed to warming in the Labrador region caused by natural climatic forcing associated with reduced sea ice cover, a weakening of the North Atlantic Oscillation (Bengtsson et al. 2004), and changes in the thermohaline circulation (Sutton and Hodson 2005). Payette suggested that due to the biogeographical history of white spruce (Ritchie and MacDonald 1986), the higher elevation of inland stands may help explain past and recent shifts in tree line position. This study supports this claim as elevation and latitude, in concert with maritime climatic influences, appear to be the primary forces creating the distinct inland turn of tree line position at approximately 56°N and 62°W. Milder maritime fall conditions allow tree growth and survival farther north at the low elevations present along the Labrador coast, whereas the maritime influence cannot compensate for cooling air temperatures at higher altitudes on the inland plateau. These two influences find an equilibrium position roughly around sites 5-7 along the Labrador tree line as the decrease in latitude allows for warmer, maritime-influenced temperatures to reach the higher elevations inland. As elevations begin to recede into Québec, tree line position resumes a more northern position as a result of decreasing elevation and renewed proximity to the oceanic conditions of Ungava Bay (Figure 2.1).

2.7. Conclusion

Currently, white spruce growth at tree line in northern Labrador is controlled by temperatures during the current growth season (Apr-Sept) and the preceding fall season (Sept-Oct) to varying degrees dependent on latitude, distance from the coast and elevation. We have described here two distinct zones (Figure 2.1) of shifting radial growth-climate sensitivity affecting tree growth at Labrador's northern tree line. Trees persisting in the 'arctic maritime' zone at the northern edge of the tree limit experience a more gradual onset of spring temperatures, snowmelt and ground thaw. These trees begin and complete their growth cycle in a relatively short time period limited by their northerly position; consequently, they most positively respond to temperatures at the height of summer, June and July.

The 'subarctic maritime' zone, encompassing the remainder of tree line sites is distinguished by a somewhat earlier arrival of spring temperatures sufficient to thaw snow cover and the active layer. This may result in some early desiccation damage to needles, but overall, it leads to an earlier start to the radial-growth year for trees in this area. June and July temperatures of the current growing season remain the most important driver of radial growth in this region, but previous and current fall temperatures are also positively contributing to white spruce growth. The spatial shifting of the climate sensitivity of trees along tree line is most likely the result of a confluence of maritime and continentally-derived latitudinal influences. Both appear to be exerting some control over the position and success of tree growth in Labrador's northern boreal forest.

The influence of the Labrador Sea in late summer and early fall on the climate of coastal Labrador allows for white spruce growth and survival farther north than inland, where rising elevation limits trees to lower latitudes. The unusual configuration of the tree line here is due to the complex interactions of maritime, latitudinal and topographic climate influences acting collectively on east-west and north-south transitions of forest-tundra. The results of this study better illuminate the possible resulting climatic conditions in these zones of confluence, where maritime and continental climate influences interact, as they exist across the boreal forest in both Europe and Russia. The appearance of shifting radial growth-climate relationships at tree line in a coastal, boreal forest setting in Labrador may offer insight into understanding the spatial pattern and climatic sensitivity of other circum-boreal regions worldwide. How might these relationships change over time or under current projected climate changes? On the basis of these findings, the previously expected straight-forward expansion and advance of global boreal tree line under warming northern conditions needs to be more closely examined.

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Tables

Table 2.1. Sampling site and white spruce tree chronology characteristics for each of the study sites in northern Labrador. MSI = mean series intercorrelation (calculated on 50-year lagged segments; values over 0.328 are significant at the 99% level); AMS = average mean sensitivity; and MCL = mean core length.

Site	Site name	Latitude (deg. N)	Longitude (deg. W)	Elevation (m asl)	Date and length of chronology	No. of cores	MSI	AMS	MCL (years)
1	Napaktok Bay	58.0436	62.7228	~45	1883-2008 (126)	40	0.581	0.194	76.5
2	Okak Bay	57.4688	62.4728	~45	1860-2008 (149)	40	0.602	0.175	79.9
3	Tasiuyak Lake	57.3822	62.2481	39	1673-2008 (336)	39	0.697	0.201	151.7
4	Kingurtik Lake	56.8363	62.6311	52	1792-2008 (217)	38	0.581	0.197	113.4
5	Tasisuak Lake	56.7830	63.0817	150	1813-2008 (196)	40	0.601	0.210	111.7
6	Anaktalik Lake	56.6238	62.7708	21	1786-2008 (223)	39	0.512	0.206	106.6
7	Diane Lake	56.4647	62.7019	340	1730-2008 (279)	40	0.663	0.239	150.9
8	Cabot Lake	56.2841	62.7603	48	1743-2008 (266)	40	0.511	0.187	128.3
9	El Grande Pond	56.2219	63.1839	~350	1683-2008 (326)	36	0.621	0.198	164.0
10	Thomas Lake	56.1991	63.9761	~465	1760-2008 (249)	40	0.623	0.202	142.4

Table 2.2. Climate station locations and elevations used in this study. Summarized are the number of months of data contributed by each station to each of the Mean Monthly Temperature (MMT) and Monthly Total Precipitation (MTP) historical datasets to produce the composite regional climate record (1940-2008).

Station name	Station ID	Latitude (deg. N)	Longitude (deg. W)	Elevation (asl)	Months of data contributed (MMT)	Months of data contributed (MTP)
Border	7110830	55.33	-63.22	464.8 m	93 (11.2%)	106 (12.8%)
Cartwright	8501100	53.71	-57.04	14.3 m	20 (2.4%)	23 (2.8%)
Hopedale	8502400	55.45	-60.22	11.9 m	94 (11.4%)	96 (11.6%)
Indian House Lake	7113280	56.23	-64.73	310.9 m	143 (17.3%)	143 (17.3%)
Makkovik	8502NHR	55.04	-59.11	69.5 m	0 (0.0%)	2 (0.2%)
Nain	8502799	56.55	-61.68	6.7 m	478 (57.7%)	458 (55.3%)

Table 2.3. A matrix of Pearson correlation r-values between the radial growth chronology of each site using a 110-year common interval of 1899-2008. All values are significant at the 0.0005 level.

	1	2	3	4	5	6	7	8	9	10
1	–									
2	0.517	–								
3	0.361	0.681	–							
4	0.533	0.468	0.651	–						
5	0.565	0.651	0.608	0.520	–					
6	0.525	0.503	0.470	0.673	0.637	–				
7	0.600	0.463	0.442	0.560	0.607	0.696	–			
8	0.544	0.581	0.587	0.740	0.601	0.656	0.616	–		
9	0.443	0.691	0.631	0.562	0.573	0.686	0.764	0.644	–	
10	0.380	0.600	0.430	0.454	0.459	0.632	0.792	0.583	0.841	–

Table 2.4. Radial growth response functions to mean monthly temperatures for the growing season (Jun-Oct), the current spring (Apr-May) and preceding fall months (Prev. Sept and Prev. Oct)(1940-2008). Shaded values indicate statistical significance at 95%, Boldface values indicate an elevated response. Sites are also listed by their new tree bioclimate zones, either arctic maritime (AM) or subarctic maritime (SAM).

Sites	Prev. Sept	Prev. Oct	Apr	May	Jun	Jul	Sept	Oct	Zone
1	**-0.207**	-0.041	**-0.296**	-0.160	0.110	0.271	-0.060	-0.031	AM
2	**-0.298**	**-0.219**	**-0.346**	**-0.220**	0.096	**0.249**	**-0.198**	-0.158	AM
3	-0.166	-0.111	**-0.280**	-0.100	0.247	0.381	-0.074	-0.061	AM
4	-0.123	-0.182	**-0.252**	-0.036	**0.198**	**0.326**	-0.147	-0.109	AM
5	**-0.194**	-0.167	-0.270	-0.172	0.440	0.383	-0.190	-0.113	AM
6	0.057	0.084	-0.245	0.046	0.343	**0.273**	0.009	0.087	SAM
7	0.144	**0.237**	-0.146	-0.059	0.305	**0.214**	0.170	0.181	SAM
8	**-0.201**	**-0.225**	-0.419	**-0.262**	0.098	**0.295**	**-0.192**	**-0.217**	SAM
9	0.121	0.137	-0.282	-0.139	**0.196**	**0.233**	0.047	0.039	SAM
10	0.165	**0.215**	-0.076	-0.060	0.171	0.185	0.116	0.096	SAM

Table 2.5. Response functions to mean monthly total precipitation for the months March to October of the current growing year (1940-2008). Shaded values indicate significance at 95%, boldface values indicates an elevated response. Sites are also listed by tree bioclimate zone, either arctic maritime (AM) or subarctic maritime (SAM).

Sites	Mar	Apr	May	Jun	Jul	Sept	Oct	Zone
1	**-0.252**	-0.142	**-0.232**	**-0.244**	0.072	0.108	-0.079	AM
2	**-0.259**	**-0.256**	**-0.265**	**-0.265**	-0.024	0.057	-0.190	AM
3	-0.144	-0.165	**-0.196**	-0.087	**-0.225**	0.179	-0.173	AM
4	**-0.203**	-0.343	-0.163	-0.066	**-0.205**	0.060	**-0.304**	AM
5	**-0.222**	-0.137	-0.325	**-0.274**	-0.041	**0.223**	0.038	AM
6	**-0.198**	**-0.251**	-0.190	**-0.261**	-0.157	0.034	-0.185	SAM
7	-0.156	**-0.218**	**-0.204**	**-0.206**	**-0.196**	0.129	-0.013	SAM
8	**-0.277**	**-0.378**	**-0.313**	**-0.224**	**-0.256**	0.004	**-0.333**	SAM
9	**-0.288**	**-0.278**	**-0.238**	-0.186	-0.108	0.006	-0.037	SAM
10	**-0.222**	**-0.270**	-0.126	**-0.228**	**-0.256**	-0.009	-0.129	SAM

Figure Captions

Figure 2.1 – A map of Labrador highlighting the approximate locations of all ten sample sites, climate stations and current tree line position (Brandt 2009). Also illustrated are the approximate boundaries of the three previously defined zones and the two newly defined tree bioclimate zones within Labrador, Canada. The continental and western part of the maritime zone were defined by Nishimura (2009), whereas the extension of the maritime zone eastward, and the delineation of the coastal hyper-maritime zone were defined by Dumaresq et al. (2010).

Cape Chidley
Labrador
Torngat Mountains
LABRADOR
SEA
Hebron
Arctic
Maritime
Québec
Nain
Indian House Lake
Subarctic
Maritime
0 100 200
kilometres
Hopedale
Border
Makkovik
Labrador
Hyper-maritime
Continental
Maritime
Churchill Falls
Cartwright
Labrador City
Happy Valley-
Goose Bay
sample sites
growth boundaries
tree line
© MUN, Geog, 2010-65

Figure 2.1.

Co-authorship Statement

The design and development of the research proposal were completed by me, with input from Colin Laroque and Trevor Bell;

The practical aspects of the research were completed by me, with logistical support by Colin Laroque, Trevor Bell, Ben Phillips, Mariana Trindade and Amanda Young;

All data analysis was completed by myself;

All manuscript preparation was completed by me with comments and editorial suggestions from Colin Laroque and Trevor Bell.

Chapter 3, "Radial growth forecasting of white spruce at treeline in Labrador, Canada" has been submitted for publication.

Chapter 3

3. Radial growth forecasting of white spruce at treeline in Labrador, Canada

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3.1. Abstract

White spruce trees (*Picea glauca* (Moench) Voss) at their northern range limit are expected to be particularly susceptible to current and ongoing changes in climate, especially in northern Labrador, Canada. This study examines past climatological relationships to the radial growth of white spruce at ten tree line sites across northern Labrador and then forecasts their future radial growth (2009 - 2100) using two different climate change scenarios. Models were constructed using a stepwise multiple regression analysis employing monthly compiled variables and the best models were selected using Akaike's Information Theory for all ten sites. The model outputs were then cross-referenced to verify key climatic variables to historic white spruce growth, and landscape-level patterns of their responses were noted. Radial-growth forecast model outputs illustrate a generally decreasing radial growth rate at extreme northern locales, and moderate radial growth increases for more southern sites by 2100 AD. However, the effects of other disturbance factors on tree line position, such as wildfire and insect outbreaks, are also likely to be modified by future warming. The radial growth forecasts produced here suggest the potential for tree line expansion inland from southern and intermediate latitude coastal sites, while no further expansion is expected at extreme northern locales along the coast.

Keywords:

Radial-growth forecasting, climate change, white spruce, *Picea glauca,* Labrador, tree line, dendroclimatology.

3.2. Introduction

Changing climatic conditions have always affected the growth, range limits and species composition of forested ecosystems across the globe. It is in northern regions where the most dramatic changes in climate have recently been observed, and are expected to continue to occur under current warming forecasts (Raisanen, 2001, Hassol, 2004, Johannessen et al., 2004, Chapin et al., 2005, Trenberth et al., 2007). The migration of tree species is also commonly predicted when the long-term effects of climate change are assessed (McKenney et al. 2007; Iverson et al. 2008). The initial ecological indicators of climate change in boreal ecosystems are predicted to be landscape-scale alterations to species composition and an altered northern tree line (Soja et al. 2007). Recently, studies conducted to forecast changes in species composition for eastern North America have shown that some tree species may be completely extirpated under certain climate change scenarios (Iverson and Prasad 2001; Iverson et al. 2008). In general, these studies commonly demonstrate a northerly migration of tree species, the displacement or elimination of some tree species, and an overall reorganization of forest composition and diversity. Indeed, the Canadian Forest Service has developed models delineating tree species displacement in response to the predicted future relocation of climate zones (McKenney et al. 2007).

Representing Canada's easternmost edge of the boreal forest, Labrador trees are under considerable climatic stress. Payette (2007) has argued that the northern Québec-Labrador tree line is the most climatically stressed tree ecosystem in eastern North America. Given this heightened sensitivity to climate, how will white spruce trees in northern Labrador respond to predicted changes in future climate? Labrador tree line is unusual in that it appears to exhibit both advancement and retreat of tree line position over short distances in recent decades (Payette

2007) and because it exhibits two regions of forest-tundra transition; a conventional north-south orientation and an irregular east-west orientation. Given these special characteristics, how will the tree line of northern Labrador respond to changes in climate over the next decades to century time scales? With the development of high resolution regional climate projections, it is now possible to assess the long-term viability of boreal tree species in a changing climate, and with it, the potential future position of tree line (e.g. Iverson et al. 2008).The primary objectives of this study are to simulate how the radial growth of the dominant tree line species – white spruce (*Picea glauca* (Moench) Voss) – may respond to two future climate scenarios for northern Labrador, to interpret this response in terms of radial growth-climate relationships and tree line ecology, and assess the implications of these responses for future tree line position.

3.3. Study Area

The shallow-rooting white spruce is the dominant tree species persisting at tree line sites across Canada (Rowe 1972; Farrar 1995) as it is ideally suited for the permafrost conditions present in northern regions. This is particularly true along Labrador's most northern forests; however, white spruce shifts to co-dominant status with a mix of black spruce (*Picea mariana* (Mill. B.S.P.) and eastern larch (*Larix laricina* (DuRoi) K. Koch) at inland locales (Payette 2007). Coastal forests eventually give rise to forests that grow on the interior plateau 200 to 500 m above sea level (asl). The interior plateau is deeply dissected by fiords and river systems at much lower elevations than the surrounding landscape. As a result, forest stands typically exist in the form of tree islands confined to lowland areas around or near a body of water, giving way to tundra vegetation at well-drained, upland sites (Payette et al. 2001).

3.4. Research Approach

Figure 3.1 illustrates the primary steps of the research approach used in this study in flow chart form. Basically, radial-growth forecasts were achieved by combining global climate modelled future climate projections with radial-growth response models. Ten response models were developed using a stepwise regression technique with tree-ring data as the dependant variable and 26 parameters of climate as independent variables. A "change factor" conversion was applied to the future climate projections in order to better represent the regional climate of the study area. This approach is more appropriate for the regional-scale perspective of this study than similar statistical downscaling approaches (Wilby et al. 2003; Diaz-Nieto and Wilby 2005).

3.4.1. Data Sources

3.4.1.1. Tree-ring chronologies

Master white spruce radial-growth chronologies were developed by Kennedy et al. (2011) using standard techniques for each of ten sites along tree line in northern Labrador between 56 to 58°N and 61 to 64°W (Table 3.1; Figure 3.2). Statistical analyses of individual and master chronologies demonstrated that (i) white spruce radial growth at treeline exhibited both strong and common sensitivities to growing conditions, (ii) a common signal was evident from individual trees at each site, and (iii) there was an identifiable shift in radial growth-climate response northward along tree line resulting in the identification of two separate tree bioclimate zones (Kennedy et al. 2011). Trees within the northern 'arctic maritime' zone, representing the upper portion of tree line, are most sensitive to temperatures at the height of summer (June-July), whereas trees within the more southern 'subarctic maritime' zone also incorporate sensitivities to spring (Apr-May) and previous fall (Sept-Oct) temperatures, in addition to summer temperatures (Kennedy et al. 2011). For the most part, however, the ten master chronologies over the common period of 1899-2008 revealed broadly synchronous periods of ring width, involving below average growth (1912-1934, 1970-1984), above-average growth (1935-1970), and increased year-to-year variability (1899-1911, 1985-2008; Figure 3.3).

3.4.1.2. Historical Climate

This study made use of a composite regional record of historical climate representative of the study area constructed from the records of six Environment Canada climate stations (Kennedy et al. 2011). This composite record relies heavily on the Nain climate station, ideally located within the study area, and spans 69 years from 1940 to 2008. The average recorded mean annual temperature over the entire length of the record was -3.4°C, fluctuating between a high of 0°C in 2006 to a low of -6.7°C in 1976. In general, the composite record illustrated colder mean annual temperatures between 1948-78 and 1986-95; and warmer mean annual temperatures between 1979-85 and 1996-2008. The average mean annual precipitation recorded over the length of the record was 761mm, oscillating between a high of 1244.6mm in 1989 to a low of 284.7mm in 1961. The composite record displayed periods of below average precipitation between 1946-57 and 1960-64; and periods of above average precipitation between 1983-90 and 1994-2008.

3.4.1.3. CGCM3.1 Global Climate Model Data

Future climate data for the tree growth forecasts relied on output from the Third Generation Coupled Global Climate Model (CGCM3.1), produced by the Canadian Centre for Climate Modeling and Analysis (CCCMA 2007). Two relatively conservative scenarios of future greenhouse gas emissions were adopted for this study from the Special Report on Emissions Standard (SRES) published by the Intergovernmental Panel on Climate Change (IPCC 2007). The SRES B1 scenario assumes a levelling off of CO_2 emissions at 550 parts per million (ppm) by the year 2100. The A1B scenario represents a less conservative estimate with CO_2 emissions levelling off at 720 ppm by the year 2100. These two models were chosen from a range of scenarios that place atmospheric CO_2 concentrations between 550 ppm and 1000 ppm by the end of this century. More extreme scenarios were not deemed appropriate for this study as the resultant changes to climate in those scenarios would deviate beyond conditions previously experienced by trees during the historical climate record.

3.4.2. Methods

3.4.2.1. Global Climate Model Calibration

Monthly climate records were generated for the grid cell bounded by 54°42' N and 57°23' N and 59°06' W and 61°27' W for the period 1900 to 2100 AD. This grid square covers much of Labrador's coastline as well as a significant portion of the Labrador Sea; however, it does not precisely overlap with the study area. The data represent average climatic conditions over the entire heterogeneous surface of the grid cell. Due to this generalized up-scaling a "change factor", based on historical climate records, was applied to the CGCM output (Diaz-Nieto and Wilby 2005). For each month of every year the CGCM3.1 monthly mean temperature and monthly total precipitation data were subtracted from the corresponding monthly Nain climate dataset for the entire length of the record (1940-2008). The resulting values were then averaged for each month over the same period, creating mean monthly divergence values. The divergence values were then re-applied to the CGCM3.1 uniform data set to shift the magnitude of the values to that of the composite regional record of historical climate, so as to not alter the seasonal variation of the forecasted future data set.

3.4.2.2. Radial Growth-climate Analysis

To establish white spruce radial growth-climate relationships in northern Labrador a stepwise regression technique, identical to previous work (c.f., Laroque and Smith 2003, Goldblum and Rigg 2005, Phillips and Laroque 2008, Girardin et al. 2008, Phillips 2009), was used. This consisted of an F-test using an "F to enter" of 0.20 and an "F to remove" of 0.25 in order to limit the number of independent variables entered into each equation. Each of the ten site's master chronologies were entered into the stepwise regression analysis as the dependent variable and three sets of climate parameters were entered as the independent variables.

Tmean: This variable set (13 variables) included mean monthly temperature for each of the growing season months (Apr-Sept) for the year of tree-ring growth (year t), and for an extended growing season (Apr-Oct) for the year prior to growth (year t-1) to account for possible late-season energy storage (Jacoby and Ulan 1982; Kennedy et al. 2011). Mean monthly temperature for winter months (Nov-Mar) were excluded both to reduce the total number of variables in this set and for ecological reasons because winter temperatures within the study area are cold enough to keep trees frozen throughout the dormant season.

Tprecip: This variable set (11 variables) included total monthly precipitation for the growing season months in which precipitation falls primarily as rain for t and t-1. These include the months of May to September for the current growing season and May to October for the previous growing season to account for possible late-season energy storage (Jacoby and Ulan 1982; Kennedy et al. 2011).

SA: This variable set (2 variables) represents mean monthly precipitation from November to May summed into a snow accumulation index for each of t and t-1. The purpose of this index is to provide a more representative perspective of the ecological effects of winter precipitation.

Previous forecasting studies have either set aside a portion of the radial growth and climate variable time series for cross-validation or have used a '10% rule' to select the variables for inclusion in the model to avoid "overfitting" (Laroque and Smith 2003, Phillips and Laroque 2007, Girardin et al. 2008). To reconcile the relatively large number of independent variables with the comparatively short climate record of this study, it was deemed necessary to maximize the length of the time series used in the regression analysis and an alternate method of model selection was adopted.

The stepwise regression process outputs a range of potential radial-growth response models consisting of increasing quantities of explanatory variables until the "F to enter" and "F to remove" values constrain the process and all potential variables are included. To select the best subset model from the range of models created, Akaike's Information Theory corrected (AICc) for models with high variable to observation ratios was used (Burnham 2002). This approach estimates Kullback-Leibler (K-L) information, in which the best model is where the K-L information or distance between reality (observed data) and the model's predictions are minimized (Burnham 2002). Akaike's Information Theory will still select the best model from the available model set, but if all the models in the set under consideration are poor, then the selected best model from this set will still remain poor.

To assess the goodness-of-fit of the AICc selected best model, an adjusted coefficient of determination (adj R^2) was used. This gives a measure of how well the model may predict future situations. The adjusted R^2 corrects the coefficient of determination for the increasing degrees of freedom resulting from additional variables being added to the model (Anderson et al. 1998). The adjusted R^2 value only increases if an additional variable explains more variability than would be expected to occur by chance.

To ensure model accuracy, two additional criteria were applied to each model prior to radial-growth forecasting. The Durbin-Watson test statistic (*d*) was employed to detect the presence of autocorrelation within model residuals and therefore imply an over- or under-estimation of the level of statistical significance. A *d* value of less than 1.0 or greater than 2.0 indicates some level of autocorrelation within a model. The Variance Inflation Factor (VIF) test quantifies how much the variance of an estimated regression coefficient is increased because of collinearity. Collinearity describes a condition where two or more predictor variables within a multiple regression are correlated. If a model returns a VIF value of >5 then the collinearity is considered too high (Kutner et al. 2004).

3.5. Results

The adjusted climate projections produced by this study for the SRES B1 and A1B scenarios demonstrate an overall generalized warming trend over historical averages for northern Labrador (Figure 3.4 and 3.5). Mean annual temperatures within the study area are predicted to rise to -0.6°C and 0.2°C by the year 2100, increases of 2.8°C and 3.6°C over the historical averages for the B1 and A1B scenarios, respectively. Furthermore, both projections illustrate that, in the future, northern Labrador will experience milder winters, earlier springs, hotter summers and warmer falls; with the A1B scenario projecting slightly warmer conditions than the B1 projection in all months (Figure 3.5). On average, northern Labrador should expect mean annual precipitation to increase by 14.5% and 16.9% according to the SRES B1 and A1B scenarios respectively (Figure 3.6). Although the seasonal pattern of variability in precipitation levels remains quite similar to historical trends, slight increases to monthly precipitation amounts were noted in both projected climates in all months (Figure 3.7). In general, the A1B projection predicted greater monthly precipitation amounts than the B1 projection.

All individual tree-ring master chronologies, model calibrations, and future model forecasts are illustrated in Figures 3.8 to 3.17. All models were calibrated over the entire length of the composite Nain climate record of 1940 to 2008. The AICc selected best models for each site chronology explained between 18.8% and 58.2% (average of 35%) of the variance in historical ring-width variability (Table 3.2 and 3.3). Despite the wide range of explained variance, each model was deemed significant with a P-value of less than 0.001. All models passed the Durbin-Watson test with values between 1 and 2. Also, all model terms passed the Variance Inflation Factor test with values below the critical threshold of 5 (Table 3.3).

Summer temperature variables (June-July) were the most commonly selected among the ten regression models. Northern sites tended to be more positively associated with warm Julys, while southern sites showed a greater positive association with warm Junes. Interestingly, springtime temperatures, particularly in April, proved very important to white spruce radial growth at six of ten sites across tree line in Labrador. Warm spring temperatures in the past have been linked to decreased radial growth (Jacoby and Cook 1981; D'Arrigo et al. 1992; 2003); this was especially true among coastal study sites along the northernmost tip of tree line. The three most inland sites (8-10) demonstrated negative associations with greater spring time snow accumulations to both the current and preceding winters. Among the more southerly sites (6-10), previous October temperatures were strongly linked to positive radial growth at four of five study locations. Spring and summer precipitation of the current growing year had a largely negative response on tree growth across all tree line sites. However, by September of the current year of growth, precipitation becomes positively linked to radial growth at several sites. The independent climate variables included in each model are listed in Table 3.4.

Table 3.5 summarizes the forecasted ring-width indices for both SRES scenarios at each tree line site. In general, modelled radial growth responded more moderately to the SRES B1 (550ppm) climate projection, than to predicted conditions under the SRES A1B climate projection (720ppm). At extreme northern sites (1-2), radial growth is largely projected to decline over the coming century. Sites 1 and 2 both report increasingly negative radial growth responses to the two SRES scenarios, while Site 3 had a neutral response to SRES B1 projection and a mildly positive response to the SRES A1B projection. Intermediate sites (4-7) demonstrated the greatest deviation from historical growth, averaging 8.8% and 17.3% increases in radial growth under SRES B1 and A1B climate projections, respectively. It is worthy of note that although the regression model projecting radial growth at site 4 was statistically significant, it only explains 18% of the variance and therefore may be the least robust of all of the models. Site 8 generated the most pronounced negative responses to both the SRES B1 and A1B scenarios at -10% and -17% respectively. Sites 9 and 10, the farthest inland, are predicted to yield small increases in radial growth to the year 2100 under both climate scenarios.

3.6. Discussion

3.6.1. Common Model Variables

By highlighting commonly selected variables from the 10 regression model outputs, a more general illustration of how white spruce trees have responded to northern Labrador's climate over the past 69 years is apparent. While not all adjacent sites share identical variables of significance, as one might think, it is important to understand that each site's trees are subject to unique growing conditions and microsite factors present at each locale. As such, nearby sites do not always share every explanatory variable, especially variables that add only small increments to the overall explained variance. One of the reasons that partials with limited explanatory capabilities might exist within individual models, is that during the sampling strategy we were forced to not consider microsite characteristics, yet they were present. Therefore any models constructed that tried to mimic individual site growth parameters, will start to bring in partials to explain these differences especially when the dominant climate parameters are already selected for modelling.

Despite the wide range of climatic influences possible to produce the radial growth forecasts, a relatively small set of variables with high explained variance repeatedly came up in model construction. This allowed for the opportunity to cross-validate and identify common variables of regional influence in the ten models in general, and eliminate the partials that may have been modelled because of spurious individual effects created by the model building processes. Therefore, the following description follows a more generalized seasonal narrative from the spring to late fall, or the beginning to end of the growing season in northern Labrador.

Trees growing at the three most southern and inland sites (8-10) were negatively correlated to greater snow accumulations indicating spring snow depths may be a limiting factor at lower latitudes inland from the coast. Higher snow loads in the spring could delay the initiation of the white spruce growth cycle by insulating the ground and thereby prolonging frozen ground conditions (Jacoby and D'Arrigo 1989; Cook et al. 2007). White spruce at six of ten sites responded negatively to warm April temperatures of the current growing year, particularly at extreme northern sites (1-3). This is likely due to desiccation damage occurring to trees at this time as a result of air temperatures rising faster than ground temperatures. As air temperatures reach levels sufficient for photosynthesis in needles, persistent frozen ground conditions can restrict the ability of roots to supply the requisite moisture resulting in the drying damage (Jacoby and Cook 1981; D'Arrigo et al. 1992; 2003).

Summer temperature variables (June-July) were the most commonly selected climatic parameter used in the ten regression models, as every regression model included at least one or the other. Radial growth at the northernmost tree line sites (1-2) tended to be more associated with warm temperatures in July, whereas growth at intermediate sites (3-5) correlated well with both June and July temperatures and warm temperatures were most linked to radial growth at southerly sites (6-10). At more southerly tree line sites, the onset of summer temperatures sufficient for the initiation of the white spruce growth cycle may be occurring earlier as a result of their lower latitude and inland position (Kennedy et al. 2011). This affords more southerly trees an earlier start to the growing season, evidenced by their association with warm temperatures earlier in the summer, than their northern counterparts. It is interesting that radial tree growth in northern Labrador has been limited by spring and summer precipitation over the last 69 years. In Alaska, the opposite has been reported; tree line white spruce growth has been limited by summer drought conditions over the past 50 years (Barber et al. 2000; Wilmking et al. 2004). It would appear precipitation amounts in northern Labrador are more than sufficient for white spruce growth, if not limiting it, contrary to the recent drought conditions experienced at Alaskan tree lines.

By September, however, the precipitation signal reverses as this month illustrates a positive relationship to radial growth at many sites. This is particularly true of northern sites where it is likely that trees in extreme northern locales are storing photosynthates at this time for the following year's growth (Jacoby and Ulan 1982). At southern sites, previous October temperatures were strongly linked to good radial growth in many models. Here it is thought that warmer fall temperatures at the lower latitude sites allows for a longer period of cambial growth extending into September, such that the production of photosynthates for use in the following growing season occurs even later in the fall.

3.6.2. Possible Future Climate in Relation to Model Forecasts

In general, radial growth across tree line had a relatively muted response, positive or negative, to the projected climatic conditions under the SRES B1 scenario (Table 3.5). However, all tree line sites demonstrated a more extreme response to the projected conditions of the SRES A1B scenario (Table 3.5). This could indicate that white spruce trees at tree line can maintain relatively stable radial growth under mild warming conditions, but would deviate more intensely with further increased warming.

A review of the radial growth forecasts produced from the regression models illustrates a generally negative to neutral trend for trees in extreme northern locales, while more southern sites are forecast to exhibit an augmented growth pattern. The overall warmer projected future conditions under the SRES B1 and A1B scenarios provides some explanation as to why these trends exist (Figure 3.4 and 3.5). Growing season length, temperature and precipitation levels, and winter snow accumulation are all forecast to increase in both scenarios (Figures 3.5 and 3.7).

The climatic variable most responsible for the negative forecasts in northern areas is April temperature. Increases from a -6.1°C average in the year 2008 to a -2.6°C average by the year 2100 caused most models using this variable to respond poorly, producing negative forecasts. The progressively warmer and more abrupt onset of spring temperatures that are forecast under the SRES scenarios will likely limit white spruce expansion in extreme northern regions where the models predicted limited, if any, increase in radial growth (Table 3.5).

Intermediate southern sites (sites 4 -7) by comparison should benefit greatly from the extended growing season length, as well as the warmer summer temperatures projected for northern Labrador. June and July temperatures are forecast to increase by an average of 2.3°C and 2.0°C respectively by the turn of the century under the SRES A1B scenario; these changes should significantly boost white spruce radial growth along southern stretches of Labrador's tree line. Sites 8 through 10 will also benefit from warmer future summer conditions; however, these sites' forecasts are hindered by projected heavier spring snow loads which could potentially limit future radial growth at these sites.

Trees at all sites should respond positively to the dramatically warmer late-summer and early-fall temperatures projected for northern Labrador. Average monthly temperature increases from 10.5°C to 13°C in August and 6.4°C to 8.3°C in September, using the SRES A1B projected climate, will dramatically extend the growing season later into the fall. Although white spruce trees across tree line will experience, to some degree, an extended growing season, the intermediate sites unhindered by spring desiccation damage or snow accumulation are positioned to benefit the most in terms of radial growth. Lastly, predicted warmer future October temperatures combined with an extended growing season should allow for a greater opportunity for the storage of energy late in the growing season to assist with radial growth during the following year (Jacoby and Ulan 1982).

3.6.3. Future Tree line Migration

With the radial growth model forecasts of white spruce across ten tree line sites in hand, it is possible to predict a potential future tree line position. It has been hypothesized that white spruce is already advancing toward its range limit located higher in altitude and latitude due to delayed postglacial migration (Payette 2007). Given that the extreme northern sites (1-3) demonstrated negative to neutral responses to both SRES scenarios, it seems unlikely that further advances to tree line will occur along the north coast. Intermediate tree line sites (4-7), however, exhibited increasingly positive responses to the two SRES scenarios, indicating a possible advance of tree line westward, onto the interior plateau, at these latitudes. Sites along the most southern stretches of the Labrador tree line (8-10) also illustrated an increase in radial growth to the future SRES conditions, suggesting a possible advance of tree line sites northward from southern inland locales. These potential inland range expansions and the likely stagnation of the northern coastal arctic limit could result in an altered tree line position by 2100 as suggested by Figure 3.2.

3.6.4. Prospective Biotic and Abiotic Ecological Disturbance

The models produced here only predict future radial-growth responses to future climatic inputs and therefore cannot account for all potential influences on radial growth. Northern ecosystems are particularly susceptible to changes in their annual energy and moisture budgets, and as such, as climate warms trees will not be the only species to shift or expand ranges. Both insect and fire disturbance is expected to increase in temperate forests as bioclimatic barriers shift in response to climate changes (Soja et al. 2007; IUFRO 2009). There is already evidence of spruce budworm defoliation at the northernmost position of white spruce in northern Labrador (Payette 2007), and insect outbreaks are expected to increase under future warming conditions (Neuvonen et al. 1999; Candau and Fleming 2005). Therefore, it should be anticipated that the future radial growth of white spruce at Labrador's tree line could be significantly affected by rates of insect disturbance generally associated with more southern areas of its current range. In addition, an overall increase in fire regimes is also expected (Flannigan and Van Wagner 1991, Stocks et al., 1998; Soja et al. 2007) with warmer summer temperature extremes forecast for the future. Wildfire has even been shown to react synergistically after spruce budworm infestations, increasing 3 to 9 years after an outbreak (Fleming et al. 2002). This too has the potential to limit the advance of tree line northward and result in an altered tree line position.

3.6.5. Uncertainty of Global Climate Models

The accuracy of the RWI forecast models created in this study are limited by the accuracy of the modelled future CGCM3.1 data and error from using a composite data set to represent the conditions at ten different site-specific locations. Error associated with the forecasted data constantly changes through time with conditions closer to present day more reliably approximated, and error-bars decades into the future becoming more and more pronounced. Conditions closer to 2100 AD become more suspect because the drivers for each SRES are harder to hold constant. Associated with the modelled error, fluctuating ocean conditions have the potential to influence the effects of ongoing climate change, temporarily weakening the effects of any regional warming (Keenlyside 2008). These uncertainties in projected warming trends are expected to affect radial growth in ways the forecast models in this study cannot account for. Furthermore, the very level of greenhouse gas derived warming that is realized over time is another hurdle to radial growth forecasting. Due to the highly unpredictable nature of anthropogenic greenhouse gas (GHG) emissions at present and into the future, it is very difficult to ascertain which SRES scenario will actually best characterize future levels of climate change. Currently, global GHG emissions are accelerating above *all* current IPCC SRES scenarios produced (Raupach et. al 2007). If this trend continues then the forecasts described and illustrated in this study may occur in a significantly shorter time frame than modelled in the initial SRES scenarios, and tree line white spruce in Labrador may experience growing conditions that they have never historically experienced before.

3.6.6. Prospective Radial Growth-Climate Thresholds

The potential exists for forecasted climatic extremes to occur that are outside the range of the historical climate records used in this study. The best example of this would be future winter precipitation falling as rain instead of snow, as this would markedly change factors relating to growth (c.f., Laroque and Smith 2003, Goldblum and Rigg 2005). Potential ecological thresholds relating to a tree's response to temperature or precipitation in a particular month may not have been reached in the past 69 years and thus would not be incorporated into these forecast models. In other words, it may be that the influence of a host of other climatic factors becomes more limiting to white spruce radial growth as the climate continues to be altered. Consequently, as the models stray into more and more extreme climate change scenarios, it is expected that their predictive capability will begin to fail. This is why the modelling of the more extreme SRES scenarios (e.g., A1F1, A2) is simply not attempted in this study.

3.7. Conclusion

This study has shown that the radial growth of the dominant tree species at tree line in Labrador is sensitive to the projected climate changes expected for that region. Across the tree line, white spruce will experience increasingly warmer and longer growing seasons throughout the coming century. The regression models forecast generally modest changes to radial growth using the predicted climate under the conservative SRES B1 scenario, but demonstrated a more intense response to the moderate SRES A1B scenario. This suggests that tree line trees will likely maintain relatively stable radial growth into the immediate future, but will deviate more intensely, especially if more dramatic acceleration of greenhouse gas emissions hastens the predicted warming.

Warmer April temperatures in the northernmost regions of tree line could cause severe desiccation damage to trees in the future; mitigating the benefits of an extended growing season.

Intermediate sites along Labrador's tree line stand to gain the most under current predicted warming scenarios. Located slightly lower latitudinally, these medial tree line sites will suffer little desiccation damage and should be able to take fuller advantage of the warmer, extended growing seasons to come. The southernmost reaches of tree line should see elevated radial growth under the predicted lengthening and warming of growing seasons, but this increased growth could be somewhat hindered by deeper snow loads expected for the same southern sites.

Warming growing season temperatures will likely also result in the migration and/or expansion of insect ranges, as well as an increase in the occurrence and severity of fires at or near tree line. These disturbances themselves have the potential to cause landscape-scale changes to the age, structure and species composition of Labrador's forests. The future health of white spruce trees, as well as the ecological services provided by the white spruce population, may depend on how these disturbances co-react to future warming.

Some tree line white spruce populations have shown the capacity for future tree line expansion. It is possible that future warming will result in an altered tree line position in northern Labrador, with intermediate coastal populations advancing into the interior and southern populations northward. Although there are many potential external and internal sources of error in these biologically based, deterministic models, it is believed that they depict the most useful outlook into future radial growth rates of white spruce and tree line position in Labrador's north. Tree line white spruce populations have proven difficult to model, but portions of their complex radial growth-climate relationship have been illuminated in this study. Important insights from this study will hopefully provide similar useful information relating to new understandings of current climatic changes on boreal tree lines.

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Tables

Table 3.1. Sampling site locations and elevations.

Site	Site Name	Latitude (Deg. N)	Longitude (Deg. W)	Elevation (m asl)
1	Napaktok Bay	58.0436	62.7228	~ 45
2	Okak Bay	57.4688	62.4728	~ 45
3	Tasiuyak Lake	57.3822	62.2481	39
4	Kingurtik Lake	56.8363	62.6311	52
5	Tasisuak Lake	56.7830	63.0817	150
6	Anaktalik Lake	56.6238	62.7708	21
7	Diane Lake	56.4647	62.7019	340
8	Cabot Lake	56.2841	62.7603	48
9	El Grande Pond	56.2219	63.1839	~ 350
10	Thomas Lake	56.1991	63.9761	~ 465

Table 3.2. Results of the stepwise regression analysis between radial growth and temperature and precipitation variables from the regional composite climate record (1940-2008). All models are significant at $p < 0.001$.

Dependant Variable	Equations
Site1	Site1 = (Apr temp * -0.002004) + (July temp * 0.033546) + (prev Sept precip * 0.001841) + (June precip * -0.00175) + (Sept precip * 0.001213) + (Aug precip * -0.00101) + (prev June temp * -0.01828) + (Constant) 0.6065
Site 2	Site 2 = (Apr temp * -0.02004) + (June precip * -0.00165) + (July temp * 0.031507) + (prev June temp *-0.02615) + (prev Sept precip * 0.00127) + (Aug precip * -0.00095) + (Sept precip * 0.000873) + (Constant) 0.730851
Site 3	Site 3 = (July temp * 0.042026) + (Apr temp * -0.01464) + (June temp * 0.027995) + (July precip * -0.00114) + (prev June temp * -0.02274) + (May precip * -0.00132) + (Sept precip * 0.001087) +

	(Constant) 0.473034
Site 4	Site 4 = (prev SnoD * -0.00025) + (July temp * 0.02444) + (prev Oct precip * -0.00162) + (June temp * 0.019121) + (Constant) 0.789012
Site 5	Site 5 = (June temp * 0.05392) + (May temp *-0.01812) + (July temp * 0.040569) + (May precip * -0.00165) + (prev July precip * 0.001088) + (Apr temp * -0.0133) + (Sept precip * 0.001296) + (Aug precip * -0.00112) + (Aug temp * -0.0239) + (Constant) 0.386738
Site 6	Site 6 = (June temp * 0.038901) + (Apr temp * -0.01761) + (June precip * -0.0013) + (Aug precip * -0.00096) + (prev Oct temp * 0.013634) + (prev Oct precip * -0.00122) + (prev May precip * 0.000862) + (Constant) 0.816323
Site 7	Site 7 = (June temp * 0.052337) + (prev Oct temp * 0.037494) + (prev SnoD * -0.0039) + (May temp * -0.02098) + (prev July temp * -0.03136) + (May precip * -0.00163) + (July precip * -0.00091) + (Constant) 1.337513
Site 8	Site 8 = (prev SnoD * -0.00021) + (SnoD * -0.00016) + (Apr temp * -0.01051) + (July temp * 0.028143) + (prev June temp * -0.02661) + (May precip * -0.00126) + (July precip * -0.00089) + (Constant) 1.061138
Site 9	Site 9 = (SnoD * -0.0003) + (prev Oct temp * 0.024561) + (prev SnoD * -0.0003) + (June temp * 0.030504) + (May temp * -0.01835) + (Aug precip * -0.0007) + (Constant) 1.070831
Site 10	Site 10 = (SnoD * -0.00039) + (prev Oct temp * 0.025076) + (prev SnoD * -0.00041) + (prev July temp * -0.02118) + (June temp * 0.019131) + (July precip * -0.00107) + (Aug precip * -0.00126) + (prev Sept precip * 0.001304) + (Sept precip * 0.000985) + (Constant) 1.409881

Table 3.3. Multiple regression model statistics for each sample site for the period 1940-2008. D-W = Durbin-Watson test statistic; VIF = Variance Inflation Factor test statistic.

Site	Number of Variables	R^2	Adjusted R^2	P-value	Degrees of freedom	D-W	VIF
1	7	0.396	0.327	<0.000	61	1.3	<1.2
2	7	0.386	0.315	<0.000	61	1.1	<1.2
3	7	0.414	0.347	<0.000	61	1.1	<1.1
4	4	0.236	0.188	<0.001	64	1.1	<1.1
5	9	0.637	0.582	<0.000	59	1.7	<1.7
6	7	0.372	0.300	<0.000	61	1.3	<1.2
7	7	0.435	0.370	<0.000	61	1.4	<1.3
8	7	0.483	0.424	<0.000	61	1.1	<1.3
9	6	0.358	0.296	<0.000	62	1.4	<1.3
10	9	0.444	0.359	<0.000	59	1.2	<1.5

Table 3.4. Independent variables included in each AICc selected multiple regression model are summarized here. Twenty-six independent variables were included in the multiple regression analysis, but only the 19 selected by a model are shown. These are listed in the side rows against the sites in the top columns. Light highlight is used to indicate a negative relationship to a variable, while dark highlight is used to indicate a positive relationship. Horizontal lines separate current year (t) from previous year (t-1) variables. The 'A' designation signifies current year, while the designation 'B' signifies a previous year variable (1940-2008).

	1	2	3	4	5	6	7	8	9	10
A-AprT										
A-MayT										
A-JuneT										
A-JulyT										
A-AugT										
B-JuneT										
B-JulyT										
B-OctT										
A-MayP										
A-JuneP										
A-JulyP										
A-AugP										
A-SeptP										
B-MayP										
B-JulyP										
B-SeptP										
B-OctP										
A-SnoD										
B-SnoD										

Table 3.5. Variability in ring width explained by each site's AICc selected model and predicted change of future radial growth under the SRES B1 and A1B projected climates.

	Explained Variability (adj R^2)	SRES B1 (550 ppm)	SRES A1B (720 ppm)
Site1	32.7%	-1%	-4%
Site 2	31.5%	-3%	-10%
Site 3	34.7%	0%	5%
Site 4	18.8%	15%	21%
Site 5	58.2%	7%	18%
Site 6	30.0%	10%	15%
Site 7	37.0%	3%	15%
Site 8	42.4%	-10%	-17%
Site 9	29.6%	2%	7%
Site 10	35.9%	1%	6%

Figure Captions

Figure 3.1 – Flowchart illustrating the basic research approach used in this study.

Figure 3.2 – A map of Labrador highlighting the approximate locations of all ten sample sites, climate stations and current tree line position (Brandt 2009). Also illustrated are most likely areas of tree line migration during the coming century as indicated by arrows.

Figure 3.3 – Standardized site master chronologies from 1899-2008. Light shaded areas indicate periods of corresponding below-average growth, dark shaded areas indicate periods of corresponding above-average growth and non-shaded area indicate periods of increased ring-width variability (see Figure 3.1. for site locations).

Figure 3.4 – Projected future and historic mean annual temperatures for the study area.

Figure 3.5 – Projected future and historic average monthly temperatures for the study area.

Figure 3.6 –Projected future and historic mean annual precipitation for the study area.

Figure 3.7 – Projected future and historic average monthly precipitation for the study area.

Figure 3.8 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 1. Historical radial growth and model calibration are also shown.

Figure 3.9 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 2. Historical radial growth and model calibration are also shown.

Figure 3.10 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 3. Historical radial growth and model calibration are also shown.

Figure 3.11 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 4. Historical radial growth and model calibration are also shown.

Figure 3.12 –Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 5. Historical radial growth and model calibration are also shown.

Figure 3.13 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 6. Historical radial growth and model calibration are also shown.

Figure 3.14 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 7. Historical radial growth and model calibration are also shown.

Figure 3.15 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 8. Historical radial growth and model calibration are also shown.

Figure 3.16 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 9. Historical radial growth and model calibration are also shown.

Figure 3.17 – Forecasted white spruce radial growth using SRES B1 and A1B conditions at study site 10. Historical radial growth and model calibration are also shown.

Figures

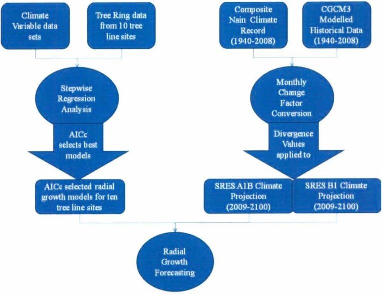


Figure 3.1.


Labrador
Cape Chidley
Torngat Mountains
LABRADOR
SEA
Hebron
Arctic
Maritime
Québec
Nain
Subarctic
Maritime
Indian House Lake
0 100 200
kilometres
Hopedale
Border
Makkovik
Labrador
Hyper-maritime
Continental
Maritime
Churchill Falls
Cartwright
Happy Valley-
Goose Bay
Labrador City
© MUN, Geog, 2010-65
sample sites
direction of
tree line advance
tree line

Figure 3.2.

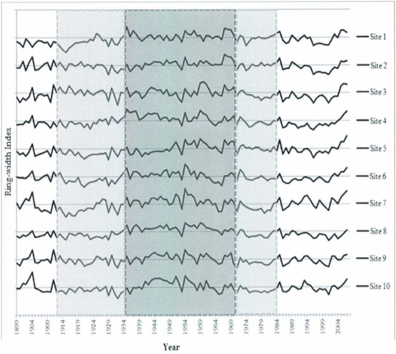

Ring-width Index
Site 1
Site 2
Site 3
Site 4
Site 5
Site 6
Site 7
Site 8
Site 9
Site 10
1899
1904
1909
1914
1919
1924
1929
1934
1939
1944
1949
1954
1959
1964
1969
1974
1979
1984
1989
1994
1999
2004
Year

Figure 3.3.

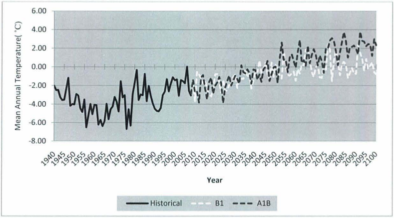


Figure 3.4.

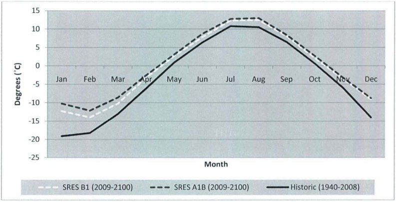


Figure 3.5.

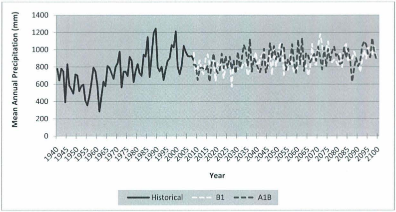


Figure 3.6.

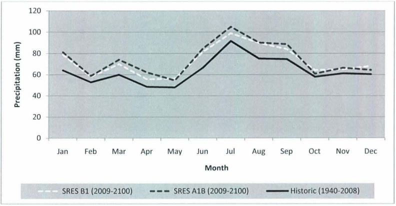
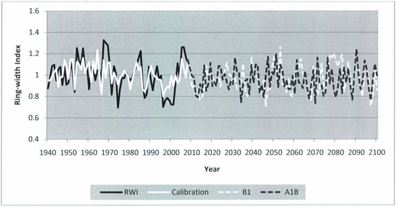


Figure 3.7.



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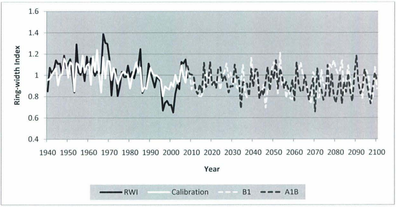

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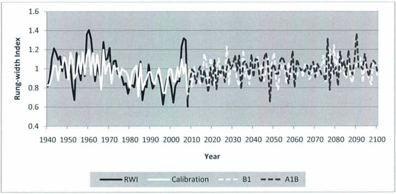

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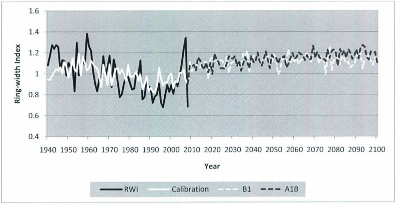

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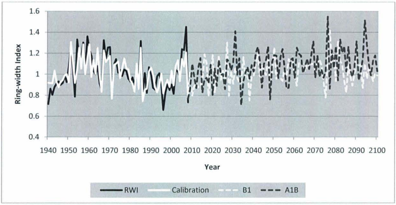

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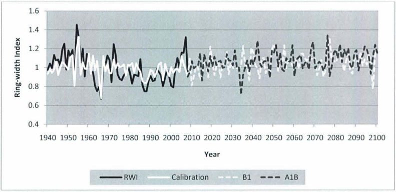

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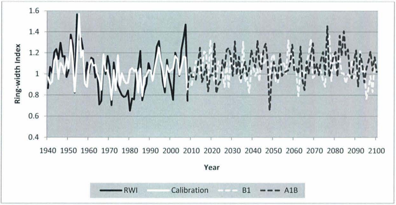

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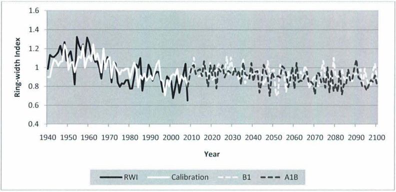

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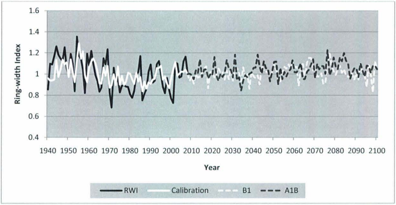

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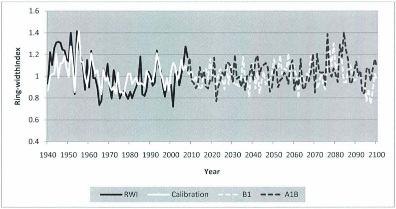

Figure 3.17.

Chapter 4.

4. Conclusions.

This thesis was the first to apply dendrochronological techniques to a network of sites spanning Labrador's tree line. It has presented annually resolved tree-ring evidence on the dominant tree species (i.e., white spruce) across tree line and has contributed to the knowledge on the radial growth response of maritime-influenced, Atlantic boreal ecosystems. This research has also answered several geoclimatic questions concerning shifting radial growth-climate relationships in northern Labrador, and therefore has filled a large spatial gap in northeastern Canada.

4.0.1 Radial growth-climate relationships

The results presented in this thesis suggest that the unusual configuration of tree line in northern Labrador is the result of continental, maritime and elevational climatic forces. At present, radial growth at tree line is controlled by spring, summer and fall temperatures of the current growing season and temperatures of the previous fall season depending upon location.

Two distinct, newly defined tree bioclimate zones in northern Labrador were observed and described. The 'arctic maritime' zone, represents the northern extension of tree growth along the north coast, and is characterized by a condensed growth cycle illustrated by positive correlations to temperatures at the height of the northern summer (June-July). The 'subarctic maritime' zone, encompassing the remainder of tree line sites, is characterized by a negative response to warm spring temperatures in the current year of growth, which likely causes moisture-stress related desiccation damage to needles. Radial growth in this zone was also positively correlated with summer temperatures (June-July) of the current growing season, but also illustrated a positive responses to current year late summer temperatures (Aug) and both previous and current year fall temperatures (Sept-Oct). These two new zones complete an already existing network of dendroclimatological analysis connecting three previously defined zones in western, central and eastern Labrador (Dumaresq et al. 2010; Nishimura 2010; Trindade et al. 2011)

4.0.2. Future forecasts and tree line position

Future forecasts of tree line white spruce using two predicted climate change scenarios highlight potential tree line advance inland, but stable to declining growth in the northernmost tree line forests of Labrador. This could indicate that the presiding assumption of straightforward advance of northern, boreal tree lines under warming conditions needs re-examination in coastally proximal regions. In fact, data in this thesis suggests that it is unlikely that tree growth will respond linearly to future predicted warming. Tree line white spruce forecasts maintain stable relationships with climate under a conservative warming scenario (SRES B1). However, under a moderate warming scenario (SRES A1B) tree line white spruce demonstrated a more dramatic response in radial growth deviation from historic growth patterns. The extreme northern stretches of coastal tree line illustrate a negative trend to future changes as warmer springtime temperatures will likely mitigate any beneficial effects of a warmer, longer growing season. Medially located tree line stands are expected to demonstrate the greatest enhancement in radial growth under the predicted future warming scenarios as a result of warmer growing season temperatures. Lastly, the southernmost tree line sites are also forecast to respond positively to future warming, but these stands will be somewhat more limited due to the likely higher snowpack depths expected in the south.

The results presented in this thesis provide valuable insight on the potential response of the dominant tree line species in Labrador to historical and future climatic change. Knowledge of the past and potential future response of boreal treeline in northeastern North America to climate change is significant due to the presence of vulnerable tundra vegetation located above the treeline, rendering it susceptible to treeline migration. These insights can provide local stakeholders with site-specific information on the potential changes to the forests of northern Labrador, with respect to climate.

4.1. References

Dumaresq, D., Laroque, C.P., and Bell, T. 2010. Tree-ring radial-growth relationships to summer temperature across a network of sites in eastern Labrador. MAD Lab report 2010-13.

Nishimura, P.H. 2009. Dendroclimatology, dendroecology and climate change in western Labrador, Canada. Master's thesis. Mount Allison University, Sackville, New Brunswick. 115 pp.

Trindade, M., Bell, T., Laroque, C.P., Jacobs, J.D., and Hermanutz, L. 2011. Dendroclimatic response of a coastal alpine treeline: a multispecies perspective from Labrador. Canadian Journal of Forest Research 41: 469-478.