University of Alberta

Treeline dendroecology and dendroclimatology, Northeastern Manitoba, Canada

by

Steven Douglas Mamet ©

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ABSTRACT

The arctic treeline is an important transition between boreal forest and arctic tundra. With a predicted high-latitude warming, many global change researchers speculate that the treeline will advance poleward. This study was an investigation of the treeline in Wapusk National Park (NP) and the Churchill Wildlife Management Area (CWMA) in northern Manitoba. There were two main objectives: (i) characterize landscape-scale responses to historical and recent climate, and (ii) assess influences of climatological variables on tree growth and regional treeline dynamics. Within upland and wetland localities around Churchill, seedling establishment and tree growth responded positively to July and September temperatures. Across Wapusk NP and CWMA, differential responses to summer temperatures were related to snowpack, with northernmost forests and central tundra trees being particularly temperature-sensitive. Results suggest considerable potential for treeline shift into tundra in response to warming. However, actual shifts will be dependent on changes in environmental variables like snowpack, permafrost and moisture.

DEDICATION

This thesis is dedicated to my Mom and Dad for always believing in me and giving me the strength and patience to complete a project like this. Your unwavering support has been a blessing throughout the duration of this research.

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CHAPTER 1

Introduction: radial growth, recruitment and treeline dynamics within the forest-tundra zone

"The reason for the renewed interest in tree lines is clear: an advancing tree line, or a denser forest below the tree line, would have important implications for the global carbon cycle and for biodiversity of the [forest-tundra] ecotone."
John Grace (2002)

Introduction

This thesis presents the results of research on tree growth and recruitment dynamics in northeastern Manitoba. The two primary research objectives were: (i) determine the stand age characteristics and recruitment history within upland and wetland environments near Churchill, Manitoba, and (ii) assess the various climatological factors affecting radial growth within Wapusk National Park (NP). Two distinct investigations were undertaken in order to meet these objectives. These were: (i) a landscape-scale age-structure analysis of treeline stands within wetlands and uplands and, (ii) a regional-scale dendroclimatological examination. Chapters two and three address the first and second objectives, respectively, while Chapter one will provide a context for the study and Chapter four will provide a synthesis of the results.

The latitudinal forest-tundra ecotone

The boreal forest is the largest terrestrial ecosystem in Canada, occupying 40% of the total land area (Ritchie 1993), with the forest-tundra component comprising 11% of the boreal forest and about 5% of the total land area. At the southern boundary of the boreal forest or the "treeline", the distribution of coniferous tree species is limited primarily by climatic moisture regimes (Hogg 1994) while tree growth at the northern treeline has been attributed to low temperatures (Szeicz and MacDonald 1995). It is necessary to point out that the treeline is not necessarily an abrupt "line", beyond which no individuals are to be found, but it represents the "northernmost position of arboreal growth" (Payette et al. 2001, p.709). Similarly, according to Pruitt (1978, p.33), the treeline is "the absolute poleward limit of trees, and is formed by different species in different areas". Pruitt (1978) gives a functional definition of a tree as an individual possessing a single central trunk with a 2 m minimum height above the mean winter snowpack.

The treeline is a prominent feature of the forest-tundra ecotone, a term first used by Clements (1936) to describe the transition zone between alpine forest and tundra communities, but now extended to describe the plant communities between the boreal forest and the arctic tundra (Payette et al. 2001). As such, the treeline is the boundary between tree growth form individuals and krummholz (stunted) trees (Payette et al. 2001).

Numerous researchers have proposed explanations for the existence of the treeline. Körner's review (1998) includes frost damage, winter desiccation and abrasion damage by wind-driven snow and ice, seed development and recruitment limited by low temperatures, short growing season and numerous combinations of these factors. Körner (1998, p.456) suggested that while these factors can modify local treeline positions, they cannot explain the global pattern and, based on a thorough examination of published studies, determined the treeline is "a thermal boundary for developmental, formative processes". Accordingly, Körner (1998) found treeline positions generally were associated with a mean growing season temperature between 5.5°C and 7.5°C. Thus, while there can be regional factors contributing to the limitation of growth by northern trees, the reduction in air temperature with increasing latitude is the primary determinant of the circumboreal treeline on a global scale.

Climate warming and treeline dynamics

Northern hemispherical and Arctic warming

Average northern hemisphere land-surface temperature has risen between 0.07 and 0.09°C decade^{-1} from 1901 to 2005, with most of the warming occurring in recent decades, and it is predicted to warm another 2.4 to 5.9°C during the next 100 years (IPCC 2007). Comparatively, the Arctic has warmed by an average of 0.09°C decade^{-1} during the same time, and is predicted to warm between 2.8 and 7.8°C over the next century (ACIA 2004). Arctic warming has been predicted to be greater during the winter and autumn when compared with summer, as temperatures are to rise 3 to 5°C during winter/autumn and < 1°C during the summer (ACIA 2004).

Warming of the Hudson Bay region

The scenarios mentioned above are similar for the Hudson Bay region (Gough and Wolfe 2001), with predictions of a mean regional temperature increase of 4.9°C based a warming of approximately 4.6°C on land and 5.1°C over the ocean (2 x CO_2 scenario). In terms of Canadian warming, the largest temperature increases are expected to be adjacent to the Arctic Ocean and Hudson Bay due to the effects of reduced duration of seasonal sea ice (Woo et al. 1992). As Hudson Bay is generally ice-covered for 11 months of the year (Gough et al. 2004; Gagnon and Gough 2005), the higher albedo of the ice reflects more incoming solar radiation, and there is a resultant delay in spring and a southern extension of permafrost along the western and southwestern coasts of Hudson Bay (Rouse 1991; Gough and Wolfe 2001). The presence of permafrost there impedes water percolation and increases latent heat flux at the detriment of sensible heat due to evaporation (Maxwell 1986).

Warming of this region would result in numerous positive and negative feedbacks. Some of the predicted positive feedbacks include: (i) earlier spring melt of sea ice and snow on land (Harding et al. 2002) and displacement of tundra by forest-tundra and boreal forest (Callaghan et al. 2002), both acting to increase absorption of solar radiation and soil heat flux, and (ii) increase in the duration of the thaw season (Gagnon and Gough 2005) resulting in soil moisture deficits and thereby more energy available for sensible heat flux. Negative feedbacks could include: (i) increased plant growth leading to increased sequestration of carbon dioxide to reduce greenhouse gas concentrations and decrease potential for atmospheric warming (Callaghan et al. 2002; ACIA 2004), (ii) increased paludification which will divert more solar radiation towards latent heat flux (Valentini et al. 2000) and (iii) increasing oceanicity from reduced ice cover during the thaw season resulting in increased evaporation and cloud formation (e.g., increased atmospheric albedo) (Crawford 2000). However, the consensus is that the net effect of the positive and negative feedbacks is positive and therefore warming is expected to continue in the decades ahead (Callaghan et al. 2002).

Forest-tundra dynamics

Research has shown that temperature plays a very important role in the position of the treeline, and the reproduction, establishment and growth of tree species within that environment (Payette and Filion 1985; Bonan et al. 1992; D'Arrigo and Jacoby 1993; Foley et al. 1994; Bonan et al. 1995; Pielke and Vidale 1995; Chapin III et al. 2000; Briffa et al. 2002). As surface air temperatures have increased considerably over the last few decades and are predicted to continue to do so (c.f. IPCC 2007), it has been theorized that the treeline will shift poleward, as has occurred during previous warm periods of the Holocene (MacDonald et al. 2000; Payette et al. 2002).

Numerous studies of treeline characteristics across the extent of the boreal forest within central and eastern Canada have produced conflicting results. Asselin and Payette (2006) found that despite climatic warming since the end of the Little Ice Age (LIA) the dominant tree species, *Picea mariana* (Mill) B.S.P. failed to re-colonize the tundra. They attributed this to insufficient seedling production from krümmholz stands in northern Quebec. As well, the seed bank in the region had been quickly depleted due to the cool climate of the last 3000 years (*P. mariana* seeds can remain viable in the cone for up to 25 years (Haavisto 1975)), further decreasing post-fire re-colonization (Sirois and Payette 1991; Asselin and Payette 2005). Conversely, *Picea glauca* (Moench) Voss successfully colonized the east coast of Hudson Bay during a mild period of the LIA, due to increased ability for sexual reproduction (Caccianiga and Payette 2006). In northern Labrador, *P. glauca* establishment peaked during the mid-20th century, with inland treelines retreating a few tens of meters; and treelines and seedling establishment within the coastal alpine tundra increasing during the 20th century (Payette 2007). It was hypothesized that the disparity in regional response of *P. glauca* to climate warming was due to impeded migration of the species inland due to topographic barriers (Payette 2007).

Vallée and Payette (2004) found that significantly shorter trees persisted during the LIA, and the growth of taller and larger trees during the 20th century was likely due to increasing temperatures. Scott et al. (1987b) reported that there had been no major change in the position of the treeline southwest of Churchill in response to climate warming, whilst there was an infilling of stands. However, during a warm period from 1920 to 1950, some forest-tundra areas were colonized by *P. glauca* seedlings resulting in the development of open forest (Scott et al. 1987b). As well, woodland formation was also attributed to the existence of wind-sheltered sites that allowed tree islands to coalesce into open forest (Scott et al. 1993). Infilling of the open forest was related to the density and size of trees that grow during initial establishment which was a response to favorable climatic conditions (Scott et al. 1987b). The timing and response of treeline changes could vary considerably between sites due to confounding effects of atmospheric warming, for example, paludification (Skre et al. 2002). Furthermore, the scale of the study can complicate interpretation (e.g., treeline heterogeneity increases as scale decreases from global to regional to landscape and so on) (Holtmeier and Broll 2005).

In light of this variability it is evident that further research is necessary to accurately assess forest-tundra dynamics in terms of treeline advance, stand infilling and enhanced tree vigor with climatic amelioration. A confounding effect of a non-linear response of treeline to climatic warming has also been noted and attributed to several factors: asexual reproduction (e.g., ramets), longevity, phenotypic plasticity and threshold effects (Körner 1998; MacDonald et al. 1998; Burkett et al. 2005; Holtmeier and Broll 2005). In other words, individual trees beyond the treeline could be relicts of past climatic regimes that have persisted through adverse conditions but are no longer in equilibrium with the present climate (Dalen and Hofgaard 2005). As well, sexual reproduction is necessary for treeline advancement and seed banks could be too depleted from adverse climate to respond linearly when climate becomes more favorable (Sirois and Payette 1991; Asselin and Payette 2005). Prerequisites of an advance of treeline are: (i) presence of seed-bearing trees and, (ii) the occurrence of seed years resulting in adequate production and distribution of viable seed (Tranquillini 1979). Thus, the existing trees must sustain enhanced growth in order to produce cones and seeds (energy expensive from an ecological perspective). Therefore the status of existing trees must be assessed in order to determine the potential for recruitment of new individuals.

Objectives and methodology

The main purpose of this research has been to examine responses of the forest-tundra ecotone to past and present climate, and to assess the potential for vegetation change on the landscape. In order to create a logical framework within which to make meaningful inferences about forest-tundra dynamics, two main questions had to be addressed:

1. How has climate affected recruitment and radial growth within the forest-tundra ecotone?
2. Have existing trees responded positively to warm episodes and what teleconnections with hemispheric climate variability have been expressed within the Hudson Bay Lowlands?

Different methods were employed to address each question and meet the study objectives. The questions required differences in approaches: (i) scale of study – regional versus landscape and, (ii) distinctive methods used to construct tree-ring width indices and their temporal resolution.

The scale of the study to address questions of stand demographics and age structure was within a 20 km radius of the Churchill Northern Studies Centre (CNSC) in northern Manitoba. The second component involved a 250 km transect from the CNSC southeast to the Nelson River.

Dendrochronology and recruitment analysis

Dendrochronology is the "science that deals with the dating and study of annual growth layers in wood" (Fritts 1976, pg.534). In years of extreme climate, a tree might not form a ring on all portions of the stem and thus the ring is “missing” or “locally absent” along certain radii (Fritts 1976). In other years a change in cell structure occurs which results in the appearance of low-area, high-density cells that resemble the boundary of a true annual ring. Thus a “false ring” or “intra-annual growth band” has been formed (Fritts 1976) that may interfere with assigning a correct calendar age to each annual ring. These false and/or missing rings must be accounted for by crossdating the individual radii with the other local samples. Crossdating is possible since similar environmental conditions have limited annual ring widths in a large number of trees resulting in synchronous ring width structure (Fritts 1976). Thus similar patterns of ring width variation can be observed and false and missing rings can be accounted for. If the absolutely-dated ring widths are used to infer information about ecological processes such as treeline dynamics, this is the science of dendroecology (Fritts 1976).

Age-structure analysis involves binning the calendar age data of trees into age classes and assessing the frequency of occurrence in each class (c.f. Dalen and Hofgaard 2005). These age-structure histograms can be developed for several plots and statistically analyzed to determine whether densities have increased, decreased or remained stable across sites/species and in turn, they can be used to determine whether there has been a change in treeline in terms of advancement, recession or stand infilling (Kearney 1982).

Within the forest-tundra environment, there are numerous site factors that can influence tree growth and seedling recruitment such as: permafrost growth and decay, snow depth, wind exposure, flooding and seedbed suitability (Scott et al.

1987a; Payette and Delwaide 1994; Osterkamp et al. 2000; Dalen and Hofgaard 2005; Asselin and Payette 2006; Vaganov et al. 2006). As well, around Churchill there is a distinct difference in plant communities between upland and wetland forests due to variations in climate, geological history, permafrost, water table and other edaphic factors (Brook 2001). Within upland environments such as a lichen spruce forest, there exists an extensive ground cover of lichens which has been found to limit the establishment of tree seedlings until burned over (Kershaw 1977; Scott et al. 1987b). Within wetland environments such as a sphagnum spruce bog there exists an extensive ground cover of sphagnum moss which can facilitate seedling recruitment (Busby et al. 1978; Morin and Payette 1984).

Thirteen sites representative of upland (n=10) and wetland (n=3) were sampled in 2002, 2003 and 2006. A total of 483 trees were measured and sampled including 266 upland and 3 wetland *P. glauca*, 40 upland and 67 wetland *P. mariana* and 46 upland and 61 wetland *Larix laricina* (Du Roi) K. Koch. Cores were progressively sanded and polished and annual rings were counted, measured and cross-dated using standard dendrochronological techniques (Stokes and Smiley 1996). Ring-width indices were generated using the Regional Curve Standardization (RCS) method as explained by Cook and Kairiukstis (1990), in order to retain low-frequency (decadal to centennial) growth trends. Age distributions and radial growth rates were computed for the 1600 to 2000 period and compared to available climate data. This investigation is presented in its entirety in Chapter two.

Tree growth/climate relationships

The branch of dendrochronology concerned with the study and reconstruction of past climate using tree rings is known as dendroclimatology (Fritts 1976). Numerous researchers have determined temperature is a common limiting factor at the northern treeline and specifically that growing season temperature is the most important factor limiting radial growth within the Subarctic Hudson Bay Lowlands (Jacoby et al. 1988; D'Arrigo and Jacoby 1992; D'Arrigo and Jacoby 1993; Girardin et al. 2005). If temperatures continue to increase and thus prolong the growing season then growth conditions could improve for trees at the northern end of the forest-tundra ecotone, but further south, they could be limited as increased evapotranspiration reduces moisture availability (Dang and Lieffers 1989). The forest-tundra ecotone extends from the continuous forest limit to the arctic treeline and trees at the northern end of this range are at the edge of their ecological amplitude (Danby and Hik 2007). These individuals are climate-sensitive and thus good candidates for evaluating climatic change impacts within the ecotone (Payette et al. 2001).

Cores from 220 trees (102 *P. glauca*, 77 *P. mariana* and 41 *L. laricina* were collected during the summers of 2002-2005 along a north-south transect through Wapusk NP and at several locations near the CNSC within the Churchill Wildlife Management Area (CWMA). Ring-width indices were constructed from 3 ecologically distinct locales along the transect: the southern forest, the central tundra and northern forest. The northern forest is similar to the southern forested area in that it is primarily open forest with patches of open peatland and shrub and sedge fens. However the northern forest is subject to considerably different growing conditions due to cool northwesterly onshore winds from Hudson Bay, which is often ice covered for 11 months of the year (Gough et al. 2004; Gagnon and Gough 2005). As well, the two forests are physically separated within Wapusk by the central TUND region where trees are primarily limited to isolated krummholz stands.

Indices from each site were standardized to remove low-frequency variance not related to climate in order to focus on annual to decadal timescales. Each index was then compared to primary and secondary climatic variables including: temperature, precipitation, snow depth, potential evapotranspiration and indices of North Atlantic Oscillation (NAO), Arctic Oscillation (AO), El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The changing effectiveness of the aforementioned climate variables on radial growth was assessed in terms of increasing distance from the coast of Hudson Bay (e.g., a decrease in Latitude). This investigation is presented in its entirety in Chapter three.

Synthesis and conclusions

Chapter four summarizes the conclusions of the research based on a synthesis of both components of the study. Key findings as well as potential for future research on dynamics within subarctic treelines are identified. It is anticipated that the data collected and information derived from each investigation will be used to discuss larger-scale modeling of forest-tundra dynamics in central and northern Canada.

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CHAPTER 2

Dendrochronology and tree colonization: comparative analysis between wetland and upland localities in northern Manitoba

Introduction

The forest-tundra zone is a large ecotone between the boreal forest to the south and the treeless tundra to the north (Payette 1983), with the contact between the two delimiting the subarctic treeline (Payette et al. 2001). Dynamics within this ecotone and potential feedbacks with climate are important elements in studies of climate change, as the treeline has been predicted to advance northward with increasing surface air temperatures (Lescop-Sinclair and Payette 1995; Rupp et al. 2000; Danby 2007; Danby and Hik 2007). Treeless tundra has a higher albedo than the boreal forest so the colonization of the tundra by trees could increase temperatures and establish a positive-feedback to amplify global warming and treeline advance (Bonan et al. 1992; Lundberg and Beringer 2005). However, due to the heterogeneity of the landscape in terms of factors such as drainage, microtopography, snow cover, competition and disturbance, broad-scale inferences about changes in treeline position are complex (Dalen and Hofgaard 2005). As well, due to tree longevity and phenotypic plasticity, treelines are not necessarily in equilibrium with the current climate and individual established trees could represent relict treeline positions (Black and Bliss 1980; Laberge et al. 2000; Hofgaard and Wilmann 2002; Dalen and Hofgaard 2005; Asselin and Payette 2006).

Numerous studies on the age structure of treeline communities have had conflicting results. Asselin and Payette (2006) found that despite climatic warming since the end of the Little Ice Age (LIA), the dominant tree species, *Picea mariana* (Mill) B.S.P., had failed to re-colonize the tundra due to insufficient seedling production from krümmholz stands in northern Quebec. As well, the seed bank in the region had been quickly depleted due to the cool climate of the last 3000 years (*P. mariana* seeds can remain viable in the cone for up to 25 years (Haavisto 1975)), further decreasing post-fire re-colonization (Sirois and Payette 1991; Asselin and Payette 2005). Conversely, *Picea glauca* (Moench) Voss had successfully colonized the east coast of Hudson during a mild period within the LIA, due to increased ability for sexual reproduction (Caccianiga and Payette 2006). In northern Labrador, *P. glauca* establishment peaked during the mid-20th century, with inland treelines retreating a few tens of meters; and treelines and seedling establishment within the coastal alpine tundra advancing during the 20th century (Payette 2007). It was hypothesized that the disparity in regional response of *P. glauca* to climate warming was due to slow migration of the species inland against topographic barriers (Payette 2007). Vallée and Payette (2004) found that significantly shorter trees persisted during the LIA, and the growth of taller trees during the 20th century was likely due to higher temperatures. Scott et al. (1987) reported that there had been no major change in the position of the treeline southwest of Churchill in response to climate warming, whilst there was an infilling of stands. However, during a warm period from 1920 to 1950, some forest-tundra areas were colonized by *P. glauca* seedlings resulting in the development of open forest (Scott et al. 1987). As well, woodland formation was also attributed to the existence of wind-sheltered sites that allowed tree islands to coalesce into open forest (Scott et al. 1993). Infilling of the open forest was related to the density and size of trees that grow during initial establishment, and that initial establishment was related to favorable climatic conditions (Scott et al. 1987).

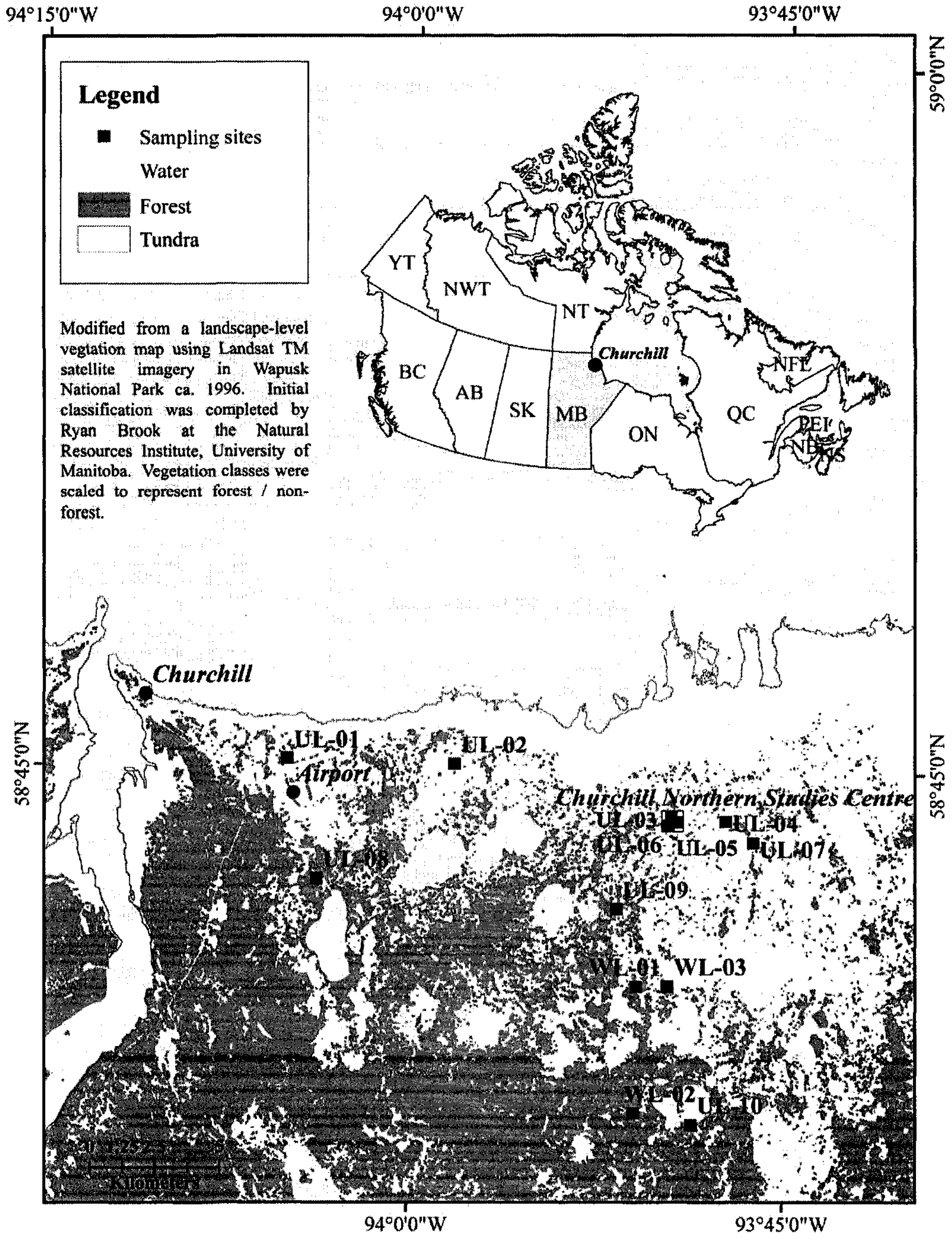
Within the forest-tundra environment, there are numerous site factors that can influence tree growth and seedling recruitment such as: permafrost growth and decay, snow depth, wind exposure, paludification and seedbed suitability (Payette and Delwaide 1994; Osterkamp et al. 2000; Dalen and Hofgaard 2005; Asselin and Payette 2006; Vaganov et al. 2006). In Churchill, there is a distinct difference in plant communities between upland and wetland forests due to variations in climate, geological history, permafrost and other edaphic factors (Brook 2001). Within upland environments such as a lichen spruce forest, there exists an extensive ground cover of lichens which has been found to limit the establishment of tree seedlings until burned over (Kershaw 1977; Scott et al. 1987). Within wetland environments such as a sphagnum spruce bog there exists an extensive ground cover of sphagnum moss which can facilitate seedling recruitment (Busby et al. 1978; Morin and Payette 1984).

Due to the disparity of results of numerous age structure and treeline dynamics studies and the inherent spatial heterogeneity of the forest-tundra ecotone, further study of tree recruitment and survival is warranted. The purpose of this paper was to describe the age structure of treeline tree communities within the uplands and wetlands in the forest-tundra ecotone and to evaluate changes in height and radial growth response with climatic change. It was expected that with a warming climate, there would be an observable increase in both seedling establishment and growth of trees (diameter and height). The specific objectives were to: (i) determine treeline response to recent and former environmental change through age structure- and tree growth-climate analyses and, (ii) examine differences in stand infilling and forest expansion within upland and wetland environments.

Materials and Methods

Study area

The study area is located in subarctic Manitoba, near the coast of Hudson Bay (Fig. 2-1). The bedrock of the area is primarily Silurian and Ordovician limestone and dolomite inland, and Proterozoic sedimentary gneiss, granitoid and quartzite near the coast (Dredge 1992). As well, sedimentary evidence of marine transgressions/regressions and Quaternary glaciations is visible within the geologic record (Dredge 1992). The nearest weather station is at the Churchill airport (lat. 58°45'N, long. 94°04'W) <1 km south of site UL-01 (Fig. 2-1) and has a mean annual temperature of -7°C, with a mean temperature of -27°C in January and 12°C in July (all climate normals cover the 1961 to 1990 period) (Environment Canada 2006). Wind is primarily out of the northwest, with maximum gust frequency (MGF) of 39%, followed by north (23%) and west (17%) (Environment Canada 2006). Any winds blowing from a 180° sector from west through north have their course over Hudson Bay which, historically, is only ice-free one month of the year (August), resulting in Arctic climatic conditions around Churchill. The growing season extends from mid-June to mid-August (Rouse 1982). Mean annual precipitation totals 557 mm, 52% of which falls as snow (Environment Canada 2006).



Modified from a landscape-level vegtation map using Landsat TM satellite imagery in Wapusk National Park ca. 1996. Initial classification was completed by Ryan Brook at the Natural Resources Institute, University of Manitoba. Vegetation classes were scaled to represent forest / non-forest.

Figure 2-1: Locations of tree core sampling. UL and WL represent upland and wetland sites, respectively.

The study site was at the northern limit of the forest-tundra in east-central Canada (Fig. 2-1). Both upland and wetland sites were sampled. Upland forests were dominated by *P. glauca* with some *Larix laricina* (Du Roi) K. Koch (tamarack) and even fewer *P. mariana*, and had a thick ground cover of lichens dominated by *Cladina* spp. (reindeer lichens) and the shrub *Ledum groenlandicum* (Labrador tea). *P. glauca* was the dominant tree species in the study area and was found almost exclusively within upland sites, as it grows best on well-drained, moist soils (Johnson et al. 1995). Wetland sites were dominated by *P. mariana* and *L. laricina* and possessed a thick ground cover of moss dominated by *Sphagnum* spp. (peat moss) and *L. groenlandicum*. As well, two sedge-fen sites were sampled (WL-01 and WL-03) that were dominated by *L. laricina*, the most common tree species found within minerotrophic sedge-fen sites toward the coast. The ground cover within the fen sites was dominated by *Carex aquatilis* (water sedge) and *Scirpus caespitosus* (tufted bulrush) with mosses. *P. mariana* individuals are uncommon within the northern part of the study area, but become dominant in ombrotrophic wetlands further from the coast.

Fieldwork

During July and August of 2006, cores were taken from trees at 13 sites within 20 km of the Churchill Northern Studies Centre (CNSC) (Fig. 2-1). At least 2 radii were removed from each sampled tree >2m in height and at least 20 trees were cored at each site (maximum of 131 at UL-10) to account for inter- and intra-tree variability. Height, diameter at coring height (DCH), vigor, disturbance, competition and microtopography (slope/aspect) were recorded for each tree. The cores collected during 2006 were supplemented by ones taken during 2002 and 2003 from a nearby *P. mariana* wetland and a *P. glauca* upland, respectively (WL-02 and UL-10 in Fig. 2-1).

Each tree was bored as close to ground level as the radius of the borer would allow, in order to estimate the maximum age. Even though determining the exact time of germination is nearly impossible, cores from near ground level give a good estimate of tree establishment (Dalen and Hofgaard 2005). For approximately 23% of the cores, some rings were missing close to the centre of the stem due to rot or failure to cross the pith during boring. In such a case, the number of missing rings was visually estimated if possible and added to the ring count. Otherwise the core was omitted from further analyses.

Laboratory processing

Cores were dried prior to being glued into core boxes. They were progressively sanded to insure all scratches were removed (Stokes and Smiley 1996). A VELMEX tree-ring measuring system was utilized to measure the width of all discernible rings in each core (0.001 mm resolution). Cross-dating was conducted (Yamaguchi 1991) and statistically validated using the program COFECHA (Holmes 1992).

COFECHA was used to calculate cross-correlations up to a 10-year lag between each individual ring-width series and a reference chronology was derived from the remaining series (Holmes 1992). All measurement series were standardized using a short cubic spline to remove low-frequency variance before the computation of the cross-correlations. Standardization is necessary in order to remove trends related to tree age and size and other low-frequency trends not related to climate (Cook and Kairiukstis 1990). Standardization of the ring-width measurement series made certain that the mean and variance of each site were comparable.

Standardized ring-width chronologies were generated using the cores collected from sites WL-02 and UL-10, as well as from within the uplands near the CNSC by Jacoby et al. (1982). The tree-ring-width chronologies were standardized using the Regional Curve Standardization (RCS) method as explained by Cook and Kairiukstis (1990). The RCS method of standardization has been found to be useful for retention of low-frequency climatic trends in tree growth (Esper et al. 2003; D'Arrigo et al. 2006). For RCS the tree-ring series were first aligned by cambial age and the mean width of all the series was computed. A cubic smoothing spline with a 50% frequency-response cutoff at 10% of the series length was fitted to the mean series (Cook and Peters 1981) and ratios of the raw ring-width data to the fitted spline were calculated. The new regional curve (RC) growth indices were then realigned by calendar year and averaged to produce the RCS-chronology. RCS assumes that the "age-aligned" series functionally describes the overall, age-related growth trend typical for the region and the mean of that series essentially represents only non-climatic, biological noise (Esper et al. 2003). Thus variations between the raw width series and the RC are interpreted as being related to climate and not any biologically-related forcing.

Data analyses

Differences between trees and between sites were examined using student t-tests in R (R Development Core Team 2006). The means of the following tree characteristics were compared: height, DCH, growth rates and age. Growth rates (GR) were calculated as GR = DCH / age. The RCS chronologies were inter-compared (running Pearson correlations within a 50-year window and lagged one year (c.f. Girardin et al. 2005)) and compared with temperature and precipitation data from the Churchill airport for the 1929 to 2002 period (response function analysis) as reported by the Adjusted Historical Canadian Climate Database

(AHCCD) (Environment Canada 2006) and the Goddard Institute for Space Studies (Hansen et al. 1999; Hansen et al. 2001) to assess their suitability for paleoclimatic reconstruction. A smaller correlation window was used for the climatic comparisons due to the short climate record. July, September and spring (March-May) temperatures were modeled using a single-variable, least squares linear regression model. Regression coefficients were bootstrapped in the statistical software R (R Development Core Team 2006) using 999 iterations over the calibration period determined by visually assessing the change in correlation with temperature over time (Fritts et al. 1991), and verified using an independent time period (Fritts 1976; Briffa et al. 1988). The temperature reconstructions were then compared to historical rates of recruitment to assess their relationship.

Results

Inter- and intra-site statistics

A total of 483 trees were cored at 13 sites (upland, n=10; wetland, n=3) (Table 2-1). All inter-site comparisons were completed at the 95% confidence level (unpaired t-test, 2-tails). No inter-site or intra-wetland comparisons were made with *P. glauca* due to a paucity of samples at the wetland sites (n=3). All tree characteristics were significantly different between sites with the exception of some similarities in age between wetland *P. mariana* and upland *P. mariana*/*L. laricina*, and wetland *L. laricina* and upland *P. glauca* (P=0.27, 0.89 and 0.19, respectively) and height of upland wetland *L. laricina* and *P. mariana* (Table 2-2). Within the wetland sites, the mean height and diameter at core height (DCH) of *L. laricina* and *P. mariana* individuals were comparable (P=0.87 and 0.76, respectively), with significant differences among the remaining characteristics

($p<0.05$) (Table 2-3). Within the upland site, mean age of *L. laricina* and *P. mariana* (P=0.48) and growth rates of all species were similar (P>0.4 for all species).

Table 2-1: Statistical characteristics of trees within upland and wetland sites

Sites:	Spp.	Trees Cored:	Mean DCH (cm)	Mean height (m)	Mean age (yrs):	Growth rate (cm yr^{-1})
Upland	All:	352	25.7 ± 6.97[a]	8.6 ± 2.22	161.9 ± 71.84	0.188 ± 0.11
n=10	*P. glauca*:	266	27.3 ± 6.97	8.9 ± 2.28	168.6 ± 68.97	0.189 ± 0.11
	P. mariana:	40	14.0 ± 2.81	6.1 ± 1.13	102.1 ± 53.82	0.180 ± 0.10
	L. laricina:	46	21.5 ± 6.08	8.6 ± 1.65	135.9 ± 82.84	0.199 ± 0.09
Wetland	All:	131	12.1 ± 3.83	7.2 ± 1.62	125.5 ± 43.35	0.110 ± 0.06
n=3	*P. glauca*:	3	11.9 ± 6.21	-	88.5 ± 19.09	0.119 ± 0.04
	P. mariana:	67	13.5 ± 3.42	6.9 ± 1.70	112.1 ± 37.15	0.120 ± 0.07
	L. laricina:	61	11.4 ± 3.76	7.9 ± 1.79	155.1 ± 58.76	0.084 ± 0.05

[a]± values represent 1σ

Ring-width

Similar age-related responses of trees were recorded at the upland and wetland sites (Fig. 2-2a). Mean ring-width was higher within the upland site, indicative of faster growing trees. Ring-width chronologies were significantly correlated between sites during the first 140 years of tree growth, with a minimum correlation of -0.70, mean of 0.64 and a maximum of 0.86 over the entire period of comparison (all significant at $p<0.05$) No correlation was observed between years 140-180 and 215-235, as well as the last decade of the comparison (Fig. 2-2(b)). The chronologies were significantly negatively correlated from years 180 to 215.

Table 2-2: Inter-site comparisons of tree characteristics (P-values)

	UL \ WL	*P. mariana*	*L. laricina*
Height	*P. glauca*	0.0000	0.0000
	P. mariana	0.0001	**0.1865**
	L. laricina	0.0057	0.0130
DCH	*P. glauca*	0.0000	0.0000
	P. mariana	0.0166	0.0092
	L. laricina	0.0000	0.0000
Age	*P. glauca*	0.0043	**0.1852**
	P. mariana	**0.2699**	0.0002
	L. laricina	**0.8934**	0.0106
Growth	*P. glauca*	0.0000	0.0000
	P. mariana	0.0019	0.0000
	L. laricina	0.0002	0.0000

*All 0.0000 values represent P-values smaller than four decimal places.

**Values displayed in bold are P-values that failed to reject the null hypothesis that the mean parameter of the species was similar ($p<0.05$).

Table 2-3: Intra-site comparisons of tree characteristics (P-values)

		Upland		Wetland
		P. glauca	*P. mariana*	
Height	*P. mariana*	0.0000*	-	-
	L. laricina	0.0477	0.0000	**0.8700****
DCH	*P. mariana*	0.0000	-	-
	L. laricina	0.0000	0.0000	**0.7593**
Age	*P. mariana*	0.0012	-	-
	L. laricina	0.0000	**0.4756**	0.0007
Growth	*P. mariana*	**0.5970**	-	-
	L. laricina	**0.6165**	**0.4140**	0.0054

*All 0.0000 values represent P-values smaller than four decimal places.

**Values displayed in bold are P-values that failed to reject the null hypothesis that the mean parameter of the species was similar ($p<0.05$).

Multi-species RCS ring-width indices

The upland RCS index covered the 1650 to 2002 period and the wetland index covered 1716 to 2002 (Figs. 2-3(a & b)). Qualitatively, the chronologies were consistent with one another from 1830 to 2002 and diverged considerably prior to 1830. Correlations within a 50-year sliding window ranged from -0.38 to 0.81, with an average of 0.41 (all significant at $p<0.05$) (Fig. 2-3c). Quantitatively, the chronologies were significantly positively correlated from 1750 to 1780 and 1890 to the end of the comparison. No significant correlation was observed between the chronologies from 1780 to 1810 and 1835 to 1890, and a significant negative correlation was found for most of the period of 1810 to 1835.

Response function analyses

Both the upland and wetland growth indices were significantly positively correlated with mean monthly July (t) temperatures at Churchill (Fig. 2-4). As well, both were negatively associated with April, May and spring temperatures. Wetland trees were positively associated with July, September, October (t-1) and summer (t) temperatures. Only upland trees had an association with precipitation: negative during October and November (t-1), February and May (t), and winter and autumn; and positive during July (t) (Fig. 2-4).

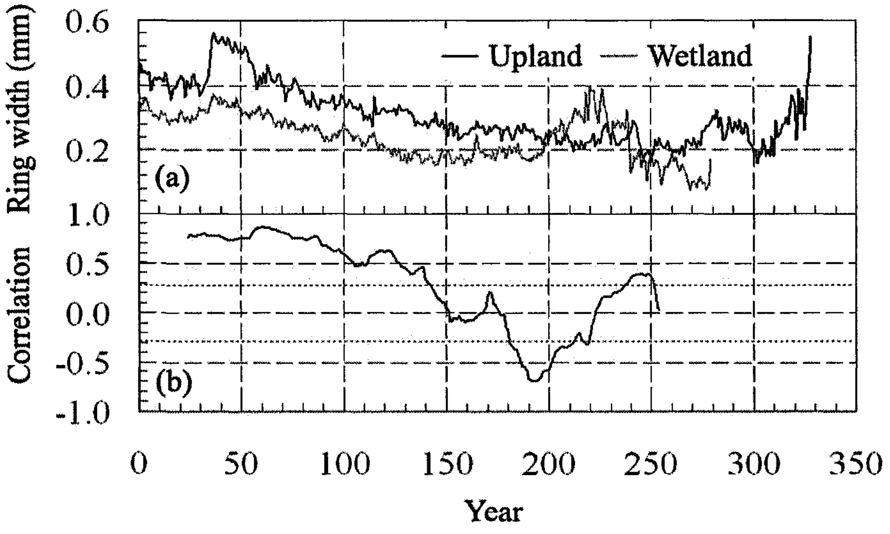


Figure 2-2: (a) Mean tree-ring-width chronologies from the upland and wetland sites aligned by cambial age and (b) 50-year window running Pearson correlation lagged by 1 year between the upland and wetland ring -width chronologies. Horizontal dotted lines indicate the 5% significance levels.

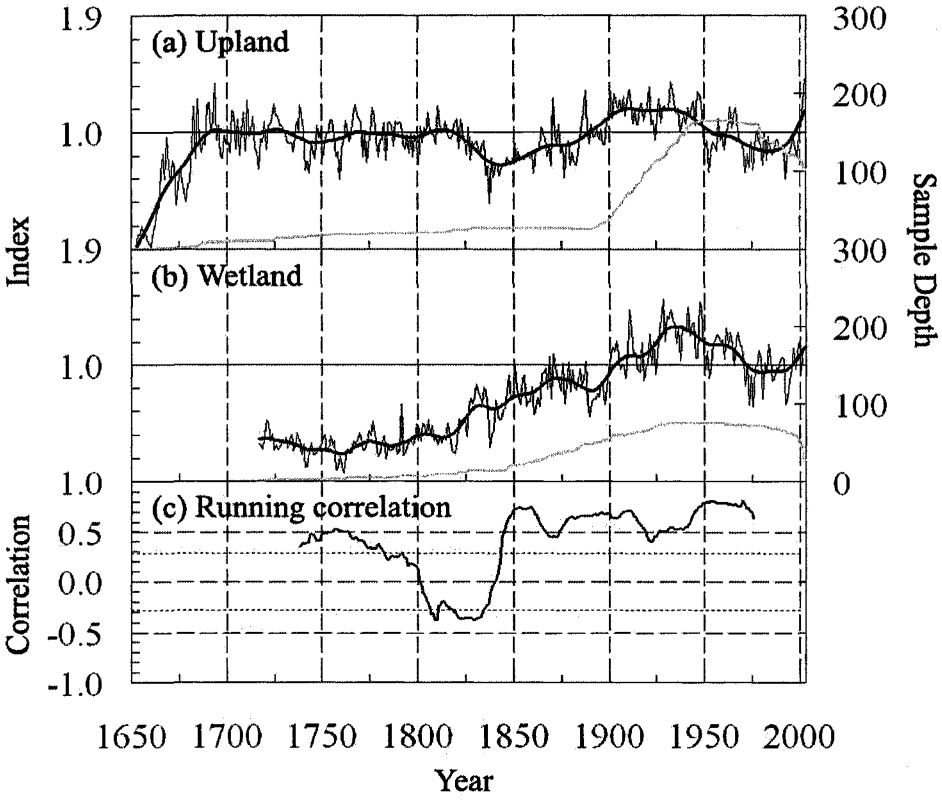


Figure 2-3: Standardized chronologies for (a) the upland and (b) the wetland sites. The thin black line is the radial growth index, the thick black line is a spline that preserves 50% of the variance at wavelengths of 10% of the chronology length, and the thick grey line is the sample depth for each chronology. (c) 50-year window running Pearson correlation lagged by 1 year between upland and wetland chronologies. The analysis runs from 1716 to 2002. Horizontal dotted lines indicate the 5% significance levels.

Temperature reconstruction

Spring, July and September temperatures were significantly correlated with tree growth at the wetland sites and have been found by previous researchers to be important climatic variables limiting tree growth (e.g., Gervais and MacDonald 2000; Briffa et al. 2002; Barber et al. 2004; Payette 2007). Therefore those variables were utilized in simple linear transfer functions for estimating temperatures at Churchill based on the wetland RCS chronology (Figs. 2-5(a – c)).

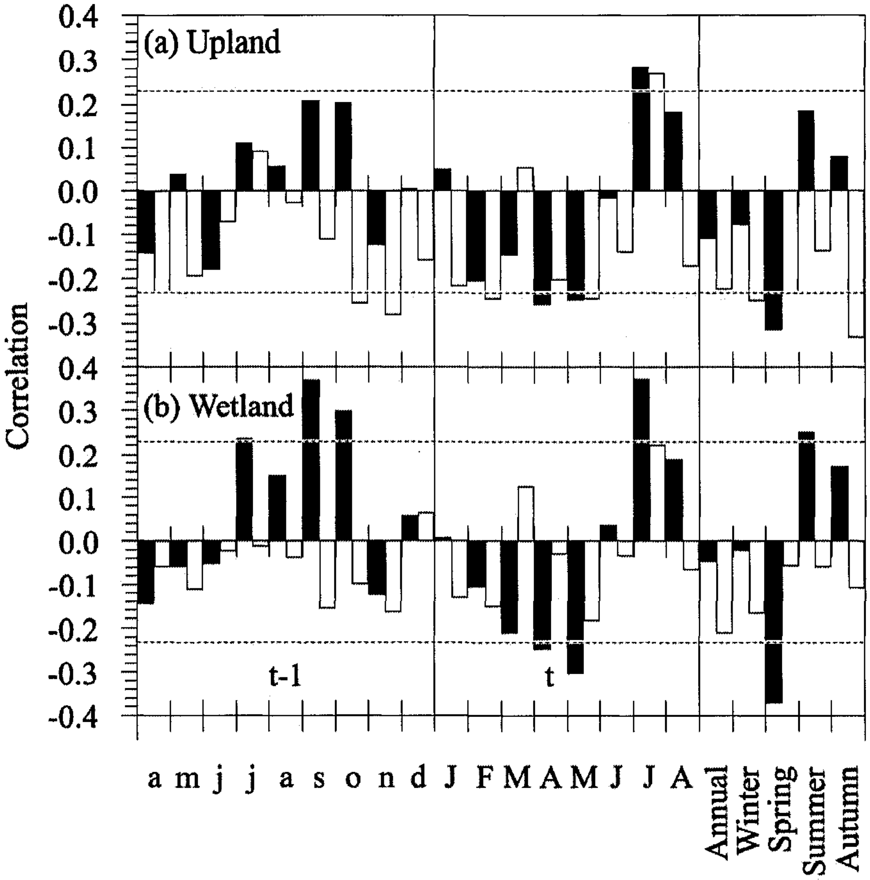


Figure 2-4: Correlation between the (a) upland and (b) wetland chronologies and mean monthly temperature (black bars) and the sum of monthly precipitation (white bars) at Churchill. Analysis runs from 1929 to 2002 and 1932 to 2002 for temperature and precipitation, respectively. Correlations were also computed seasonally where the annual values are taken as the mean/sum of September of the year preceding growth (t-1) to August of the current year growth (t); winter values include December of year t-1 to February of year t; autumn values include September to November of the year t-1; and summer consists of June through August of year t. Correlation coefficients of magnitude greater than ±0.23 (horizontal dotted lines) are significant at $p < 0.05$.

Both the late-calibrated July and early-calibrated spring temperature reconstructions passed the reduction of error (RE) and coefficient of efficiency (CE) verification tests with positive values, indicating validity in the reconstructed temperatures (Briffa et al. 1988). The early September reconstruction, despite having a significant verification correlation ($r=0.66$, $p<0.01$), failed the RE and CE verification tests, but was only slightly negative (Table 2-4). However, the RE can be susceptible to error due to notable low-frequency variations in the predictand data (temperature) (Briffa et al. 1988). Failure of the models of the first difference sign test (Fritts 1976) indicated that they were quantitatively better at characterizing low- as opposed to high-frequency variation (D'Arrigo and Jacoby 1992). The low-frequency variability of the July and September reconstructions was qualitatively consistent with the observed temperatures, with a gradual increase from the mid-1850s to 1925, followed by a brief plateau and subsequent decline to the mid-1970s, and then an abrupt increase during the early 1980s to present. The low-frequency variance of the spring reconstruction was visually consistent with that of the actual data, with values increasing to 1950, decreasing to the late 1960s, then increasing to a peak in the late 1970s, and decreasing again to the mid-1990s. Recent high temperatures (e.g., the most recent decade or two) were not mirrored in the reconstructions, with the exception of September temperatures (Fig. 2-5(f)). As well, the spring reconstruction greatly overestimated temperatures during the late 19th century when compared to the scattered instrumental record during that time (Fig. 2-5(a)).

Table 2-4: Calibration and verification statistics for temperature reconstructions

Model	Calibration period	Calibration r	r^2 (adj)	Verification period	Verification r	RE	CE	Sign test (+/-)
				July (t)				
Early	1945-1974	0.57**	0.31	1975-2002	0.47*	-0.15	-0.26	17/13 (fail)
Late	1975-2002	0.47*	0.19	1945-1974	0.57**	0.30	0.20	16/10 (fail)
Full	1929-2002	0.37**	0.13	-				
	Model:							
	1945-1974	July T=4.687[index]+6.623						
	1975-2002	July T=3.033[index]+8.862						
	1929-2002	July T=5.651[index]+6.798						
				September (t-1)				
Early	1929-1965	0.28	0.05	1966-1995	0.66**	-0.04	-0.06	18/19 (fail)
Late	1966-1995	0.66**	0.41	1929-1965	0.28	-1.07	-1.10	15/15 (fail)
Full	1929-2001	0.35**	0.11	-				
	Model:							
	1929-1965	September T=3.118[index]+2.005						
	1966-1995	September T=7.574[index]-1.726						
	1929-2001	September T=3.232[index]+2.296						
				Spring (t)				
Early	1929-1958	-0.43*	0.15	1959-1988	0.67**	0.27	0.25	8/22 (fail)
Late	1959-1988	-0.67**	0.44	1929-1958	0.43*	-0.32	-0.37	12/18 (fail)
Full	1929-2002	-0.36**	0.11	-	-			
	Model:							
	1929-1958	Spring T=-4.497[index]-5.398						
	1959-1988	Spring T=-6.904[index]-3.556						
	1929-2002	Spring T=-3.515[index]-6.757						

r	Pearson correlation coefficient
RE	Reduction of error statistic (positive values are considered a pass of the verification test)
CE	Coefficient of efficiency (positive values are considered a pass of the verification test)

*Significant at $p<0.05$

**Significant at $p<0.01$

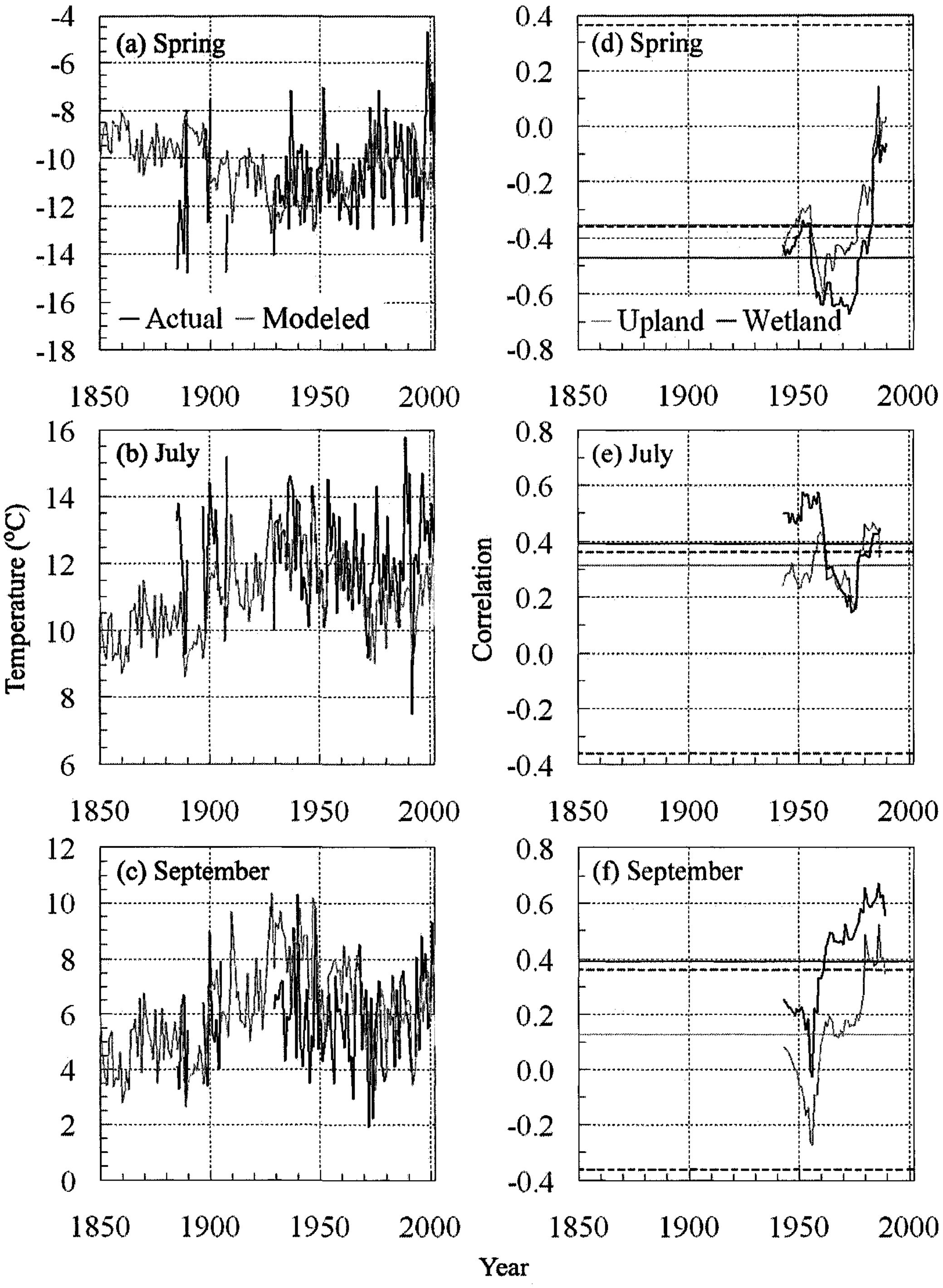


Figure 2-5: (a - c) Actual and modeled temperatures at Churchill based on the RCS index at site WL-02. Spring temperatures are the March to April mean and September temperatures are the mean of the previous year (t-1). Species included were *Picea glauca*, *Picea mariana* and *Larix laricina*. (d - f) 30-year window running Pearson correlation lagged by 1 year between the upland and wetland RCS chronologies and temperatures at Churchill. Horizontal solid grey and black lines indicate the mean of the correlations. Horizontal dashed lines indicate the 5% significance levels (r=±0.36). Note the change in scale for the correlation axes.

Age distributions

The age of the trees within the upland sites was unimodaly distributed for all species (Fig. 2-6). Recruitment was greatest from 1875 to 1940 and peaked around 1905 for *P. glauca*, 1900 to 1960 with a peak around 1900 for *P. mariana* and 1920 to 1965 with a peak around 1930 for *L. laricina* within the upland sites (Figs. 2-6(a – c)). As well, recruitment peaked during the first decade of the 1900s for all upland species as a whole (Fig. 2-6(d)). Recruitment was highest from 1880 to 1925, and peaked in 1925 for *P. mariana* (Fig. 2-6(e)). Recruitment peaked in 1850 for wetland *L. laricina*, with a secondary peak around 1900 (Fig. 2-6(f)). The highest rates of recruitment were observed between 1850 and 1930, with a peak around 1900 for all species (Fig. 2-6(g)). Correlations between recruitment at each site ($r=0.23$, 0.30, 0.61 for *P. mariana*, *L. laricina* and all species together, respectively) were significant for all species ($p<0.01$).

Within the upland sites, the oldest ages were 346, 219 and 261 years for *P. glauca, P. mariana* and *L. laricina*, respectively. The youngest ages were 30, 29 and 43 years in the same order as above. Wetland ages were 110, 279 and 265; and 75, 53 and 64 years (same order as upland sites). Additionally, dated upland *P. glauca* trees spanned the period from 1660 to 2006, *P. mariana* from 1787 to 2006 (1716 to 2006 in the wetland) and *L. laricina* from 1745 to 2006 (1741 to 2006 in the wetland) (Fig. 2-7).

Growth rates

Radial growth rates were significantly higher within the upland sites (Table 2-1). Additionally, upland *P. glauca* growth was significantly correlated with DCH ($r=0.35$, $p<0.05$), as was growth of wetland *P. mariana* ($r=0.75$, $p<0.05$) and *L.*

laricina (r=0.68. $p<0.05$) (Figs. 2-8(a & b)). There was no correlation between growth rates and DCH for upland *P. mariana* or *L. laricina*.

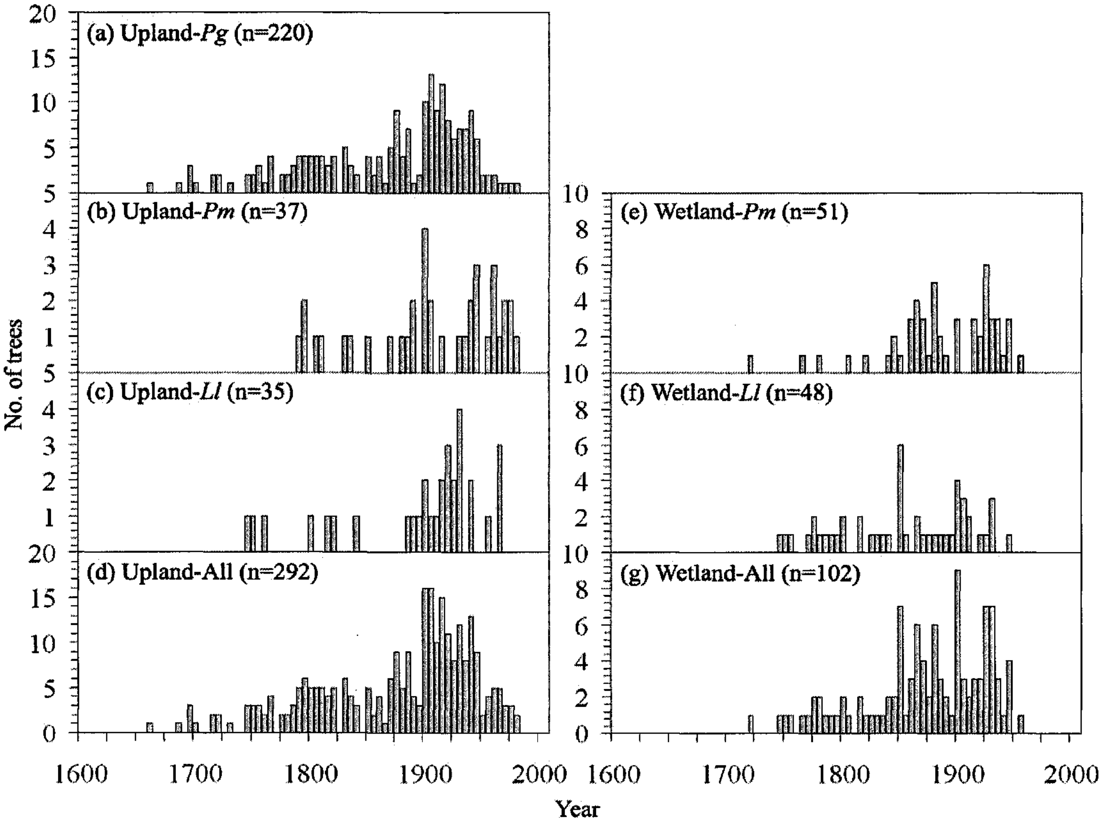


Figure 2-6: Age structure (20-year classes) of the upland and wetland study sites. *Pg* = *Picea glauca*, *Pm* = *Picea mariana*, *Ll* = *Larix laricina* and all represents the data from all species. Note the change in scale between sites.

The rate of radial growth increased every century for all species at all sites (using GR = DCH / age for individuals established within the corresponding century) (Figs. 2-8(c & d)). Additionally, the growth curves of all species at all sites appear exponential, indicating acceleration in the increase in rate of growth, with the exception of upland *P. glauca*. However, in order to account for potential bias due to aging (e.g., negative exponential age curve), growth rates within centennials were also calculated from the ring-width chronologies using individuals established during the corresponding century. As such, growth rates were still found to have increased for all species across all sites, with the exception of upland *P. glauca*, in which growth slowed from the 18th to 19th century (Figs. 2-8(c & d)). Moreover, the rate of increase in growth with time was linear, as opposed to exponential.

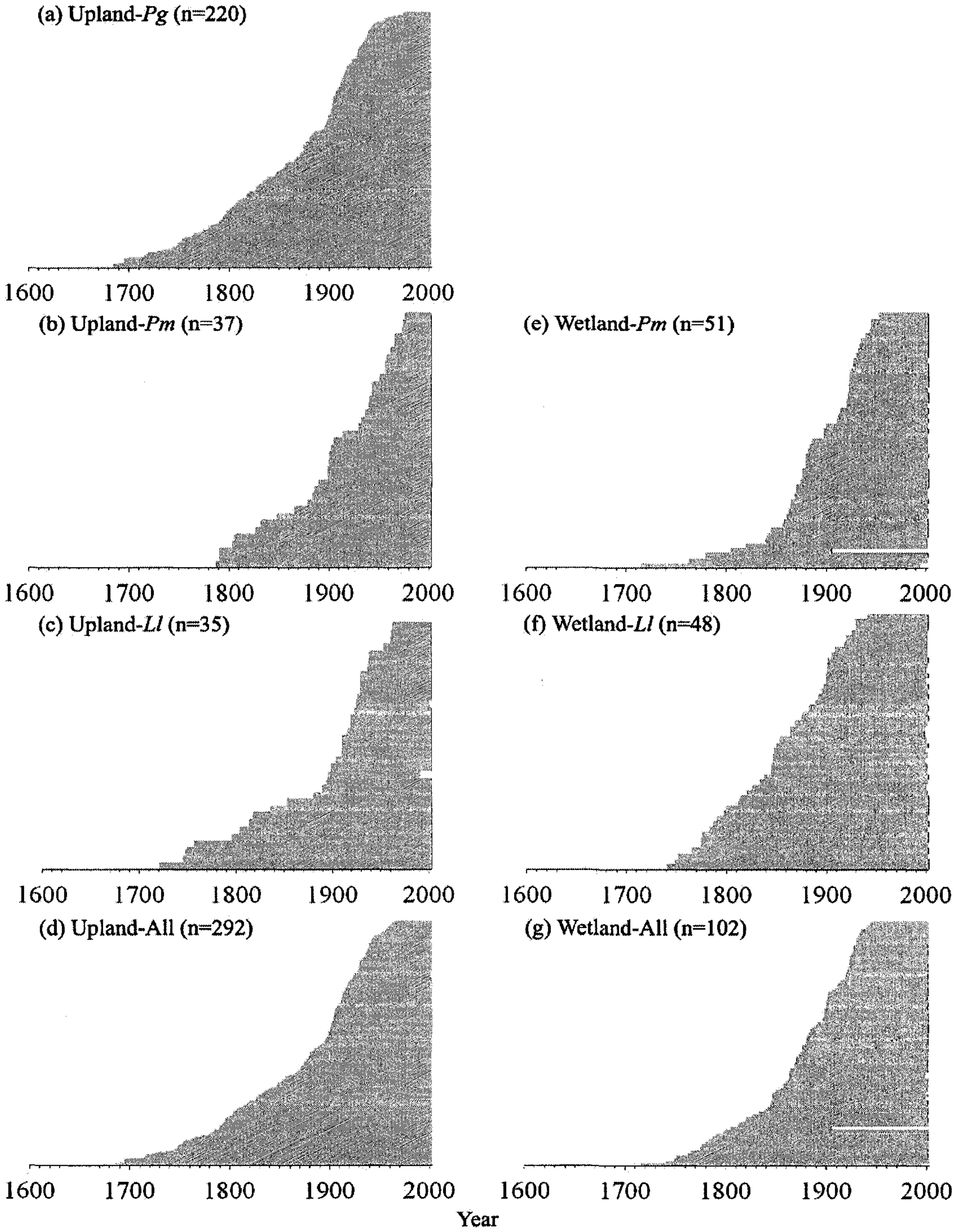


Figure 2-7: Live periods of cross-dated trees within the study areas. (a-d) Upland sites including *P. glauca* (*Pg*), *P. mariana* (*Pm*), *L. laricina* (*Ll*) and all species, respectively. (e-g) Wetland sites including all species in the same order as the upland with the exception of *P. glauca* due to paucity of samples (n=3).

A peak in tree height occurred near the beginning of the 20th century for all species across all sites (Figs. 2-8(d & f)). The tallest individuals and corresponding establishment dates at the upland site were as follows: *P. glauca* – 22.2m from 1907, *P. mariana* – 9.1m from 1806, but next tallest was a 8.3m individual dating from 1951 and 8.2m from 1899, and *L. laricina* – 14.4m from 1919. The tallest individuals and establishment dates at the wetland sites were: *P. mariana* – 11.1m from 1924 and *L. laricina* – 11.0m from 1900.

Temperature change and recruitment

Tree recruitment was compared to actual and modeled temperatures (Figs. 2-9 to 2-11). Correlations were computed for the period of overlap between the 5-year means of actual and modeled temperatures (1930 to 2000, n=15) and the age structure data grouped into 5-year bins. Actual spring temperatures were significantly correlated with the upland establishment of *P. mariana* ($r=-0.59$, $p<0.05$), while modeled spring temperatures were significantly correlated with upland establishment of *P. glauca* ($r=-0.81$, $p<0.05$), wetland establishment of *P. mariana* ($r=-0.72$, $p<0.05$), and upland and wetland establishment of *L. laricina* ($r=-0.64$ and -0.55 at $p<0.05$, respectively) (Fig. 2-9(b)). Modeled July temperatures were significantly correlated (0.55 and greater, $p<0.05$) with establishment at all sites, with the exception of upland *P. mariana* (Fig. 2-10). Actual July and September temperatures were not correlated with tree recruitment. However, modeled September temperatures were significantly positively correlated with establishment of all species at all sites with the exception of upland *P. mariana* and wetland *L. laricina* (Fig. 2-11). When establishment of all species was compared to modeled temperatures, significant correlations were observed for both upland and wetland sites for all three temperature reconstructions (Figs. 2-9 to 2-11). As well, reconstructed July and September temperatures were qualitatively consistent with recruitment of all species at all sites, with the exception of wetland *L. laricina* which did not appear "in phase" with temperatures. Additionally, spring temperatures did not qualitatively compare with rates of recruitment (Fig. 2-9).

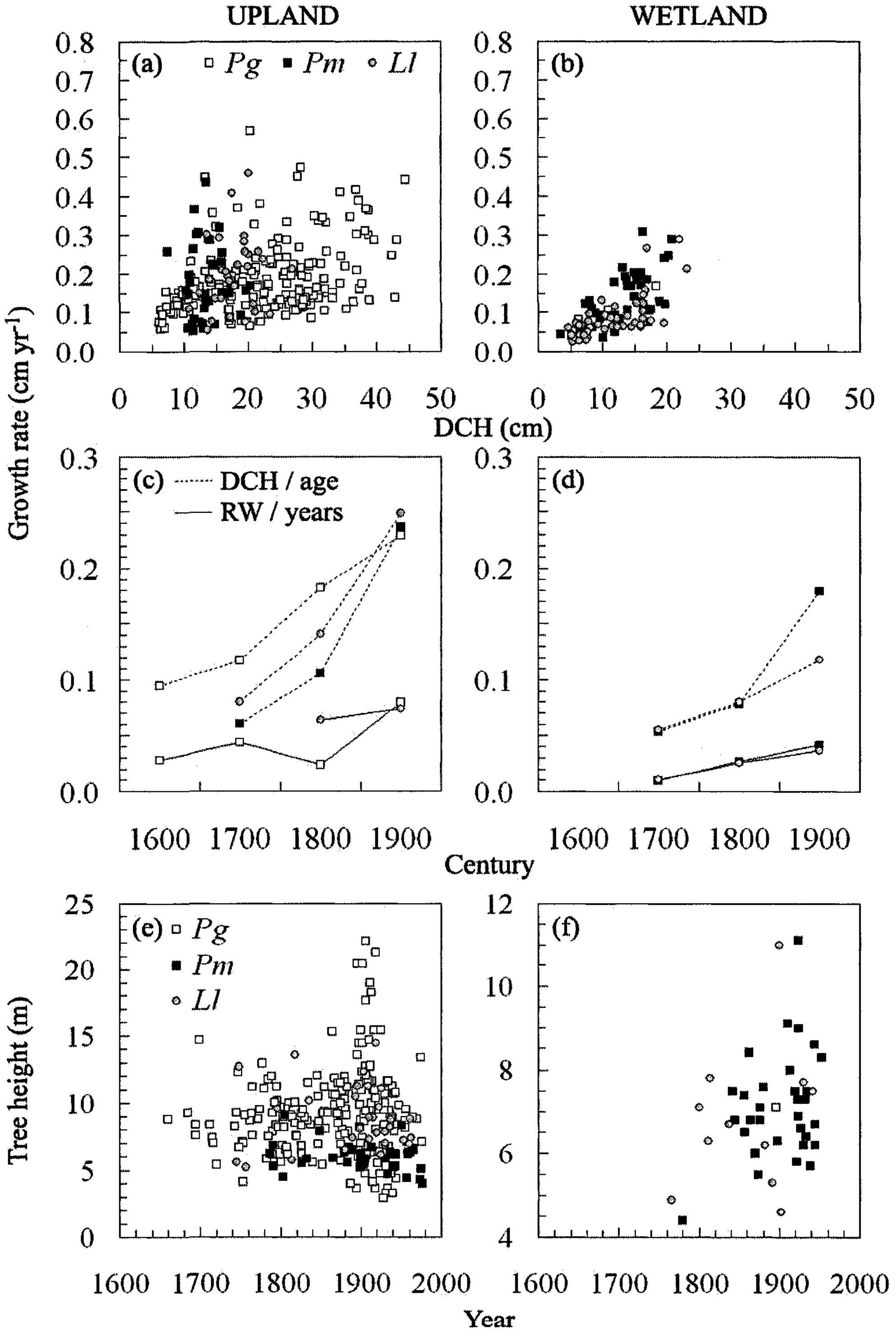


Figure 2-8: (a & b) Relationship between tree mean radial growth rate and DCH at the upland and wetland sites. (c & d) Mean growth rate during each century for each species. Mean growth rate for individuals established during the corresponding century (dotted line) (calculated as growth rate = DCH / age) and mean growth rate calculated using ring widths during each century from sites UL-10 and WL-02 (solid line). (e & f) Relationship between tree height and the year of tree growth initiation at the upland and wetland sites. *Pg* = *Picea glauca*, *Pm* = *Picea mariana* and *Ll* = *Larix laricina*. Note the change in tree height scale between sites.

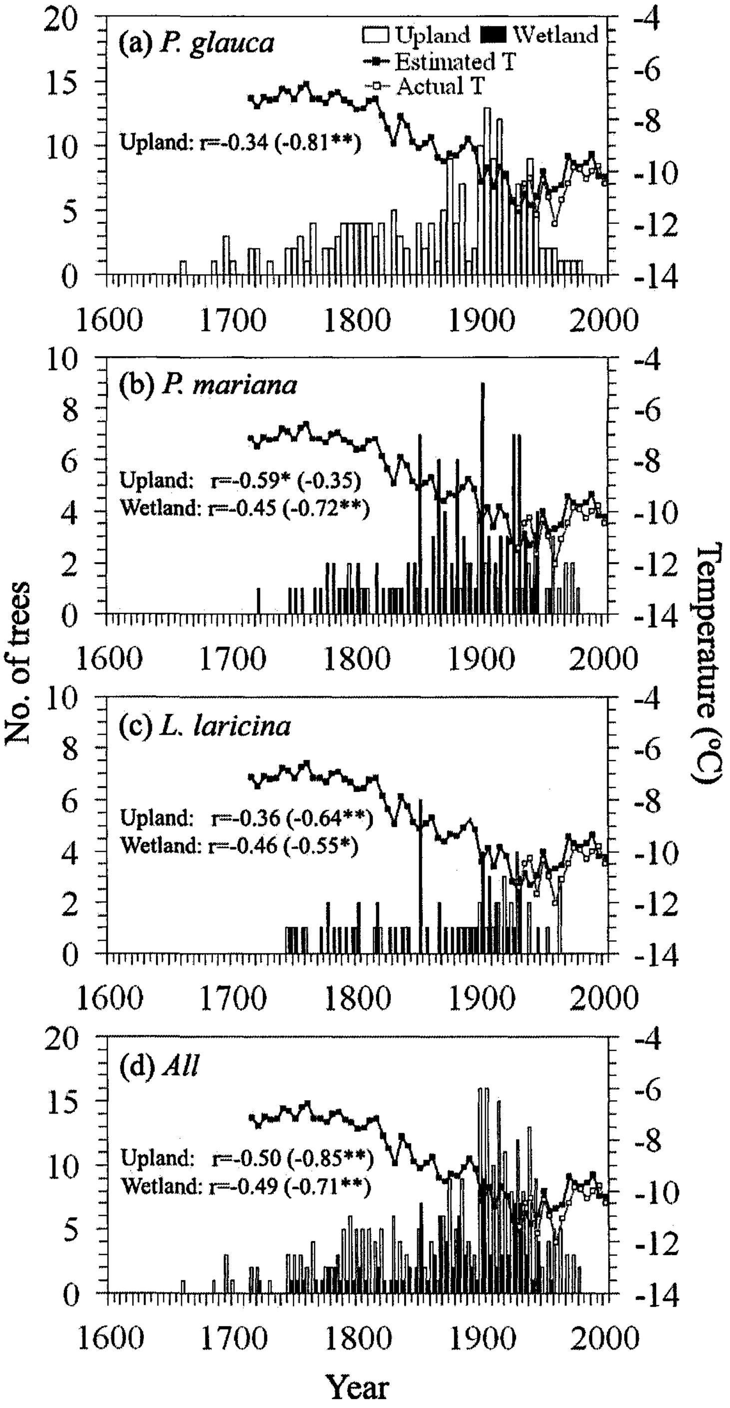


Figure 2-9: Age structure (5-year classes) of upland and wetland sites compared with spring (March-May) temperatures (5-year means) and temperature estimates derived from the wetland RCS chronology. (a) *Picea glauca*, (b) *Picea mariana*, (c) *Larix laricina* and (d) all trees combined at each site. Each data point on the thick black/grey line represents the mean spring temperature during each 5-year age class. Correlations (r) between actual (modeled) temperatures and tree establishment (1930 to 2000 period) (*p<0.05 and **p<0.01 significance). Note the change in scale for the left y-axes.

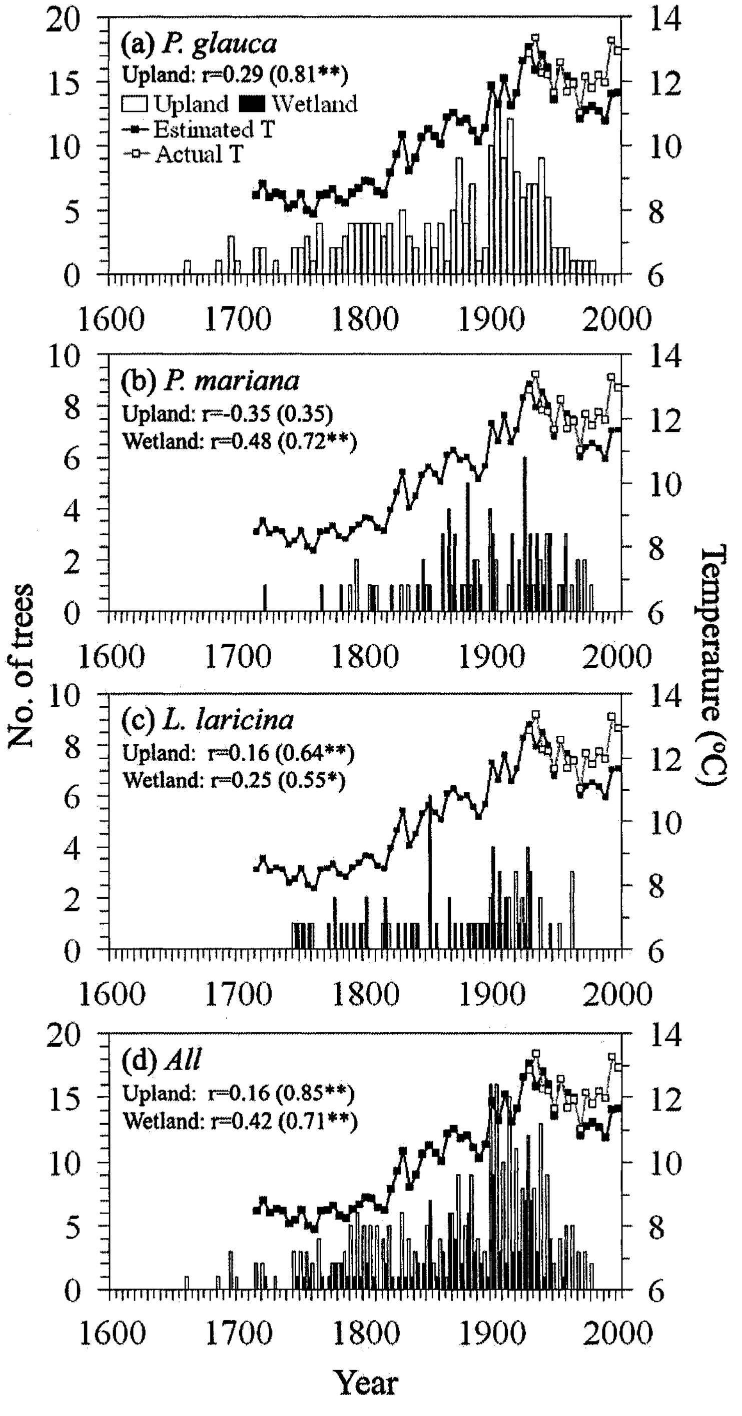


Figure 2-10: Age structure (5-year classes) of upland and wetland sites compared with July temperatures (5-year means) and temperature estimates derived from the wetland RCS chronology. (a) *Picea glauca*, (b) *Picea mariana*, (c) *Larix laricina* and (d) all trees combined at each site. Each data point on the thick black/grey line represents the mean July temperature during each 5-year age class. Correlations (r) between actual (modeled) temperatures and tree establishment (1930 to 2000 period) (*p<0.05 and **p<0.01 significance). Note the change in scale for the left y-axes.

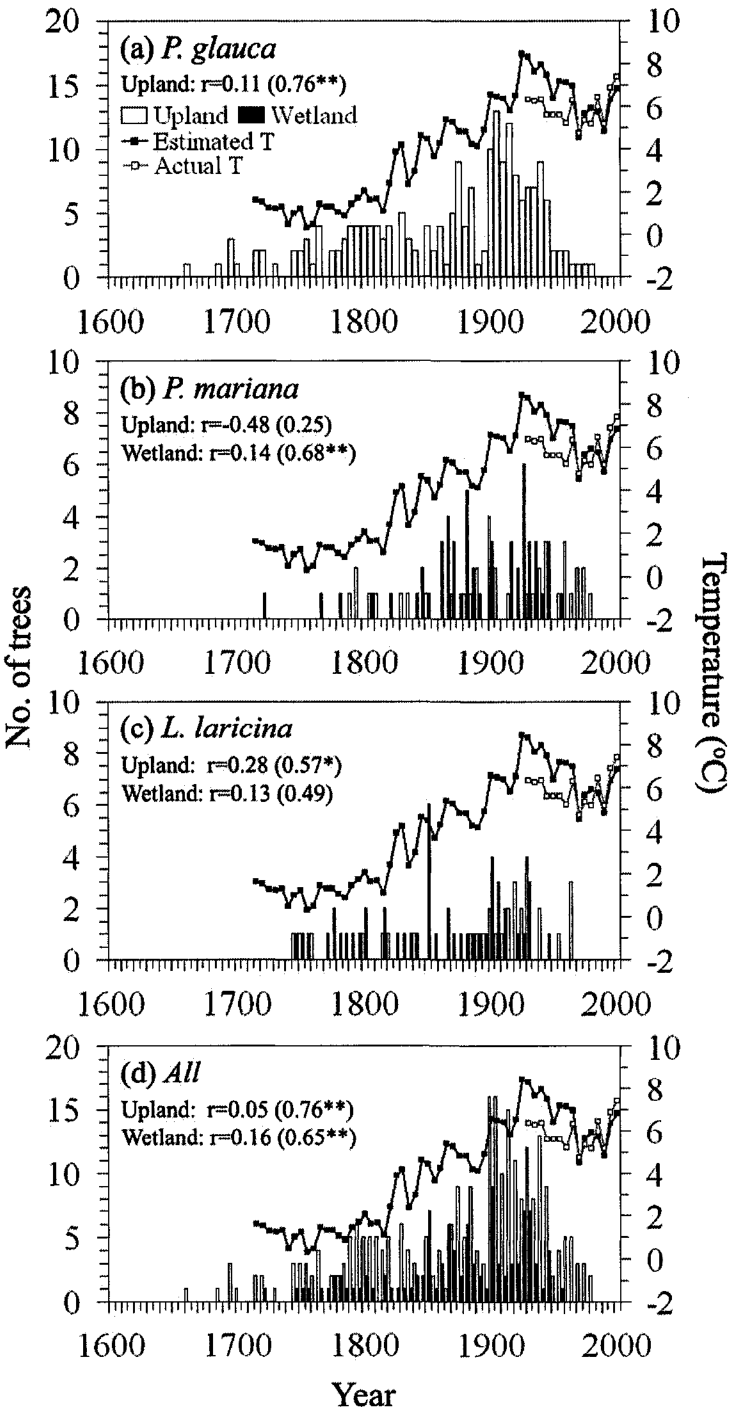


Figure 2-11: Age structure (5-year classes) of upland and wetland sites compared with September (t-1) temperatures (5-year means) and temperature estimates derived from the wetland RCS chronology. (a) *Picea glauca*, (b) *Picea mariana*, (c) *Larix laricina* and (d) all trees combined at each site. Each data point on the thick black/grey line represents the mean September temperature during each 5-year age class. Correlations (r) between actual (estimated) temperatures and tree establishment (1930 to 2000 period) (*p<0.05 and **p<0.01 significance). Note the change in scale for the left y-axes.

Discussion

Inter- and intra-site tree characteristics

Tree characteristics at upland and wetland sites were significantly different across sites in terms of means of diameter, height and growth rate. These differences were likely the result of differing growing conditions (Peñalba and Payette 1997) at each site. For example, poor conditions (e.g., hydric soils) at the wetland sites could limit the maximum size of trees (Boucher et al. 2006), while at the upland sites such limitations were not present. Additionally, snowpack variations among hummocks within the wetland sites (Kershaw and McCulloch 2007) could affect tree growth. Similar ages were observed between some upland/wetland species: *P. glauca*/*L. laricina*, *P. mariana*/*P. mariana* and *L. laricina*/*P. mariana* (Table 2-2). This is probably related to a long fire-cycle in excess of 558 years in the Churchill area (Monson 2003). The age distributions of each species at each locale indicates that fire has not appreciably influenced the sampled stands in over 300 years, as an inverse J-shaped distribution would be more indicative of post-fire colonization (Van Wagner 1978). Within sites, the mean age and growth rate of *L. laricina* was similar to that of *P. mariana* (Table 2-3). Within wetland sites this could be due to the fast-growing nature of *L. laricina* being offset by the presence of competition (due to shade-intolerance) (Burns and Honkala 1990) resulting in slower rates of growth. Within upland sites, the open canopy supports strong vigor of *L. laricina* resulting in relatively fast growing trees (Table 2-1), which could explain why the growth rates of all three species were similar (Table 2-3) and why *L. laricina* heights were comparable to *P. glauca*.

Tree-growth response to climate

Similar ring-width chronologies indicate that similar environmental forcings dominate the wetland and upland sites (Fig. 2-3). As well, the significant correlations with temperature for each RCS index suggests that trees at each site responded similarly to temperature within the majority of the last 75 years and potentially the last 150 years if we can assume the response to temperature was similar prior to the instrumental record (Briffa et al. 1998) (Fig. 2-4). Prior to 1830, the upland and wetland RCS indices diverge qualitatively and statistically (Fig. 2-3), possibly due to drought during the LIA (Dean and Schwalb 2000) as there have been continental-scale droughts in North America in the past (Stahle et al. 2007). It is plausible that due to drought, trees within the better-drained upland could suffer decreased vigor due to drought, particularly during July (Fig. 2-4) when trees complete the majority of earlywood production.

September (t-1), July (t) and spring (t) temperatures were found to significantly influence tree growth (Table 2-4), but only the July and spring wetland RCS reconstructions of temperature passed statistical verification. The underestimation of recent temperatures by the July and spring reconstructions is a hemispherical phenomenon visible in the dendroclimatic record since around 1986 (D'Arrigo et al. 2006). This could potentially be related to several factors: moisture stress (Groisman et al. 1994; Jacoby and D'Arrigo 1995; Barber et al. 2000; D'Arrigo et al. 2004; Wilmking et al. 2005), a change in response from mean or minimum to maximum daily summer temperatures (Wilson and Luckman 2003), increased winter precipitation leading to delayed snowmelt and initiation of radial growth (Vaganov et al. 1999), increasing competition and/or insect herbivory (Fleming and Volney 1995), changes in UV-B or solar radiation incident at the earth's surface (Bryson and Goodman 1980; Deluisi et al. 1994) or any combination of these factors. Despite reduced sensitivity of tree growth to summer temperature in recent years, it appears that spring and September temperatures are becoming increasingly important to the radial growth of trees as indicated by a considerable increase in correlations over the past several decades (Fig. 2-5(d – f)). With increasing temperatures the growing season lengthens (Jozsa et al. 1984), so spring and fall temperatures can become more important as minimum temperatures increase, thereby reducing the risk of early or late growing season frost damage (Colombo 1998; Jonsson et al. 2004).

Recruitment and climate

Recruitment rates peaked across all sites around the beginning of the 20th century, for all but one species (wetland *L. laricina*) (Fig. 2-6). The timing of this occurrence has been described as a continent-wide phenomenon (MacDonald et al. 1998a). This period of enhanced recruitment coincides with a large-scale sudden northern shift of the mean position of the Arctic front (Scott et al. 1988; Hofgaard et al. 1999). This shift allowed for a higher frequency of occurrence of warm air of southern origin at the northern limit of the boreal forest around Churchill (Scott et al. 1988) which could favour seedling establishment. However, when recruitment was compared to actual and modeled temperatures, few significant correlations were observed with actual temperatures, while modeled temperatures were repeatedly significantly correlated (Figs. 2-9 to 2-11). There are several plausible explanations for this: (i) the instrumental record for Churchill is short (continuous coverage 1929 – present) and when the climate data are binned into 5-year classes, the number of observations is artificially decreased resulting in lower degrees of freedom and consequently higher critical correlation coefficients; (ii) The height threshold for sampling was 2m, resulting in decreased frequency classes for the youngest individuals during the post-1950 period and a lack of representation for what is likely a J-shaped age distribution (Dalen and Hofgaard 2005). This combined with an underestimation of recent temperatures by the dendroclimatic reconstructions would result in higher correlations between the latest underestimated temperatures and lower correlations with actual temperatures - an inappropriate comparison of temperature and recruitment after 1950. While quantitative evaluations of recent recruitment proved unfruitful due to limitations within the dataset, qualitative assessments appear useful as a first approximation of the response of recruitment to temperature, as the character of the July and September reconstructions were consistent with historical rates of recruitment.

Height and radial growth

Mean growth rates increased each century across all sites and for all species with few exceptions (Fig. 2-8). This is indicative of increased temperatures resulting in increased vigor of trees at both upland and lowland sites. As well, trees which established around the beginning of the 20th century have grown taller than in the previous 250 years, particularly *P. glauca* (Fig. 2-8(e & f)). A similar tendency was observed on the eastern coast of Hudson Bay in Quebec, and was hypothesized to be related to enhanced snow trapping with increasing stand density (Arseneault and Payette 1997), and thus more protection for seedlings enabling them to grow faster with reduced wind desiccation and abrasion. Similar changes in growth from the LIA to present have been found throughout the circumpolar boreal forest (Kullman 1986a; 1986b; 1998; Payette et al. 1989; Szeicz and MacDonald 1995; MacDonald et al. 1998b).

Warmer temperatures during the 20th century likely played the most important role in the height growth of trees established at the beginning of the 20th century. Vallée and Payette (2004) found that *P. mariana* ramets established in the same forest environment following the LIA were significantly taller than those established before the 19th century. They concluded that the lower growth performance of trees living during the LIA was caused by reduced photosynthate availability due to increased frequency of bud mortality and attrition of foliage above the snowpack from mechanical loss of needles during more severe LIA winters. Several researchers have investigated the effects of genetics on variations in tree-growth form (Clausen 1963; 1965; Grant and Mitton 1977; Davis 1980; Rogers et al. 1999; Fang et al. 2006). Results differed among the studies, but generally environmental factors were more important in determining growth form than genotype (e.g., environment-induced phenotypic plasticity). However, the presence of significantly taller, younger trees juxtaposed against shorter, older trees around Churchill does suggest that there may exist multiple genotypes, at least one of which is more adept to increased height growth under climate warming than others (Davis 1980). Evaluation of this hypothesis is beyond the scope of this study but it does warrant further investigation in future studies. Other researchers suggest this increase in height could be the transition from stunted krummholz to tree growth form (Gamache and Payette 2004), and is likely to increase establishment at the treeline due to a concomitant shift from vegetative reproduction (layering resulting in ramets) to enhanced sexual reproduction (MacDonald et al. 1998a; Sirois 2000). However, there is a caveat to faster tree growth in that longevity increases with decreasing growth rate (Boucher et al. 2006) and there is potential for loss of regenerative capabilities due to earlier senescence.

Conclusions

It was found that wetland trees were more sensitive to temperature fluctuations while upland forests were more susceptible to drought. Tree vigor increased in the last several decades while tree height increased during the past century, possibly reflecting a change from stunted growth forms to arborescent individuals. This transformation can also increase reproductive capabilities of trees, a characteristic which could be the last obstacle in successful colonization of the tundra by forest (Sirois and Payette 1991; Asselin and Payette 2005). In addition, historical rates of recruitment have not differed considerably between upland and wetland sites ($r=0.61$, $p<0.05$) indicating that ground cover (e.g., lichens at uplands versus mosses at wetlands) did not significantly influence establishment prior to 1950, under the assumption that the ground cover has not changed considerably during the study period. Therefore the conditions have been set for advancement of the treeline into tundra around Churchill. However, characterization of establishment rates following 1950 is necessary to make informed predictions on the future status of the treeline.

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CHAPTER 3

Radial-growth response of forest-tundra trees to climate, Northern Hudson Bay Lowland, MB, Canada

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Introduction

The Arctic treeline at the limit of the forest-tundra ecotone is an important biogeographical boundary in terms of climate change investigations. The Arctic front oscillates over this ecotone, creating the gradation between the taiga to the south and the tundra to the north, and is reflected in the shift from boreal to tundra taxa (MacDonald et al. 1998). The position of the arctic treeline has been linked with the position of the arctic front (Beringer et al. 2001; Scott et al. 1988). It has been speculated that arctic warming could displace the position of the arctic treeline poleward from its present location as has occurred previously during Holocene warm periods (MacDonald et al. 1998). This could have significant impacts on the ecosystems within this ecotone as changes in habitat (Scott and Stirling 2002; Stirling and Derocher 1993), fire cycles (Arseneault and Payette 1992; Kasischke and Turetsky 2006) and synoptic climate (Pielke and Vidale 1995) occur in response to climate change in this sensitive ecotone (Payette et al. 2001).

Numerous researchers have concluded that growing season temperature is the most important factor limiting tree-ring radial growth within the Subarctic Hudson Bay Lowlands (D'Arrigo and Jacoby 1993; D'Arrigo et al. 1992; Girardin et al. 2005; Jacoby et al. 1988). If temperatures continue to increase and thus prolong the growing season then growth conditions could improve for trees at the northern end of the forest-tundra ecotone, but further south, they could be limited as increased evapotranspiration reduces moisture availability (Dang and Lieffers 1989). The forest-tundra ecotone extends from the continuous forest limit to the arctic treeline and trees at the northern end of this range are at the edge of their ecological amplitude (Danby and Hik 2007). These individuals are climate-sensitive and thus good candidates for evaluating climatic change impacts within the ecotone (Payette et al. 2001).

Increasing trends in northern hemisphere extratropical climate (e.g., temperature) have been observed over the last 30 years and have been linked to a shift in the dominant mode of the regional North Atlantic Oscillation (NAO) and more hemispherical scale Arctic Oscillation (AO) toward more positive values (Hurrell et al. 2001; Thompson and Wallace 1998). This upward trend in the so-called Northern hemisphere Annular Mode (NAM) has been related to decreasing sea-level pressure (SLP) over the Arctic, a colder stratospheric polar vortex persisting longer into spring, increased surface air temperature (SAT) over Eurasia and North America and a change in regional precipitation patterns (Cook et al. 1998; Cullen et al. 2001; Déry and Wood 2004; Gough et al. 2004; Lloyd and Fastie 2002; Ostermeier and Wallace 2003; Thompson and Wallace 1998), which could have implications for radial growth of trees in the north (D'Arrigo et al. 1993; D'Arrigo et al. 2003). Despite decreasing effectiveness poleward (Hare and Mantua 2001), other hemispheric-scale patterns of climate variability such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), could also lead to alteration of radial growth and flowering dates of plants

(D'Arrigo et al. 2005; Hurrell et al. 2001) through their influence on climatic variability (Mantua et al. 1997), as the Hudson Bay lowlands are dominated by air from the Pacific 33% of the time (other air masses include: 40% Arctic, 5% Atlantic, 15% Southern and 7% Hudson Bay) (Rouse 1993).

The first objective of this study was to characterize spatial and temporal variations in tree-ring radial growth in Wapusk National Park (NP) and the adjacent Churchill Wildlife Management Area (CWMA). The second objective was to assess the viability of the tree-ring record for paleoclimatic reconstruction for the Northern Hudson Bay Lowlands.

Materials and Methods

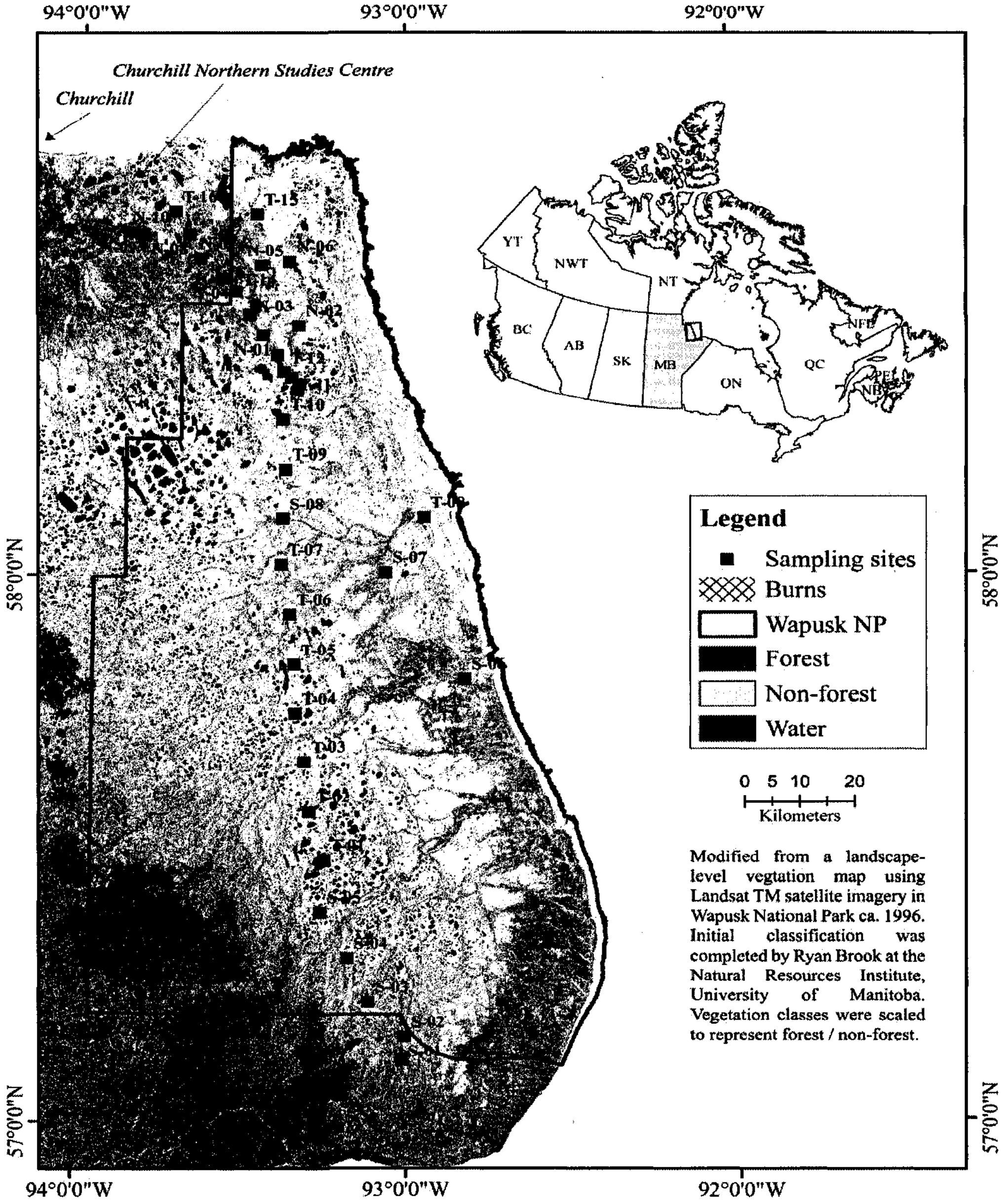
Study area

The study area extends from just north of the Nelson River in south-west Wapusk NP to the edge of the tundra in the North (Fig. 3-1). As such it was a transect through the long-axis of the Park with additional sampling along the treeline, more-or-less parallel to the Hudson Bay coastline. The southern portion (SFOR) of the CWMA and Wapusk NP is primarily open forest dominated by *Picea glauca* (Moench) Voss (white spruce) and *Picea mariana* (Mill) BSP (black spruce). *Larix laricina* (Du Roi) K. Koch (tamarack) becomes more common as conditions change from upland forest and wetland bog/forest to fen. In these wetlands the lower accumulations of peat nearer the coast occur in the more minerotrophic fens (Brook 2001; Dredge 1992; Payette et al. 2001). The central region of the park (TUND) is primarily open peatlands with forest ranging from isolated krummholz individuals to patches of open forest. Riparian forests are common in the central region where river banks are more favorable to recruitment due to increased drainage (Lloyd et al. 2003). The northern portion of the region (NFOR) is similar to the southern forested area in that it is primarily open forest with patches of open peatland and shrub and sedge fens. However an important ecological barrier separates the two forests in the form of the central TUND region where trees are primarily limited to isolated krummholz stands. As well, the NFOR locale is subject to considerably different growing conditions due to frequent, cool northwesterly onshore winds from Hudson Bay (Rouse 1991), which is often ice covered for 11 months of the year (Gough et al. 2004; Gagnon and Gough 2005).

Fieldwork

During the 2004 field season, the northern portion of the sampling transect was completed from the CWMA southeast into Wapusk NP (Fig. 3-1). In 2005 the transect was extended across the interior peatlands and into the continuous forest zone of Southern Wapusk NP. Samples collected from the northern portion of the CWMA were supplemented with cores collected during 2002 and 2003 in the vicinity of the Churchill Northern Studies Centre (N-09 and N-10 on Fig. 3-1).

Sample sites were visited by helicopter at 5 and 10-km intervals (2004 and 2005 respectively) and at least 2 (2004) or 3 (2005) trees were bored to extract 2 cores from each. In addition, cross-sectional disks or "cookies" were cut from dead snags. Since the intent of this work was to cover the CWMA and Wapusk NP, the sample size was kept small in order to ensure complete coverage within time and budget constraints. For pursposes of analysis, study sites were grouped into the three distinct zones – NFOR, TUND and SFOR.



Modified from a landscape-level vegtation map using Landsat TM satellite imagery in Wapusk National Park ca. 1996. Initial classification was completed by Ryan Brook at the Natural Resources Institute, University of Manitoba. Vegetation classes were scaled to represent forest / non-forest.

Figure 3-1: Locations of tree core sampling from three areas: NFOR, TUND and SFOR, abbreviated as N, T and S respectively.

Laboratory processing

Cores were dried prior to being glued into core boxes. They were progressively sanded to insure all scratches were removed (Stokes and Smiley 1996). A VELMEX tree-ring measuring system was utilized to measure the width of all rings in each core (0.001 mm resolution). Cross-dating between cores was conducted (Yamaguchi 1991) and statistically validated using the program COFECHA to account for missing and false rings, while chronologies were compiled using ARSTAN (Holmes 1992).

COFECHA was used to calculate cross-correlations up to a 10-year lag between each individual measurement series and a reference chronology was derived from the remaining series. All measurement series were standardized using a short cubic spline to remove low-frequency variance before the calculation of the cross-correlations (Holmes 1992). Standardization is necessary in order to remove trends related to tree age and size and other low-frequency trends not related to climate (Cook and Kairiukstis 1990). Standardization of the ring-width measurement series ensured that the mean and variance of each site were comparable.

The standardized growth indices were converted into residual standardized indices by means of averaging using residuals from autoregressive modeling of the standardized measurement series (Legendre and Legendre 1998). The residual indices possess a strong common signal without persistence (Cook and Holmes 1986). In addition, the mean sensitivity of each series was calculated. The sensitivity index can range from 0 (no differences between successive ring widths) to 2 (every second ring missing) with larger values indicative of considerable high-frequency variance (Fritts 1976). The residual chronologies were compared to climate data obtained from the Adjusted Historical Canadian Climate Database (AHCCD) of Environment Canada for the Churchill (lat.

58°45'N, long. 94°04'W) and Gillam (lat. 56°21'N, long. 94°43'W) areas during the 1929-2002 and 1943-2002 periods, respectively (Environment Canada 2006). Correlations were also calculated between the chronologies and annular modes/hemispheric climate variability: El Niño Southern Oscillation (ENSO) (Wolter 2007), Pacific Decadal Oscillation (PDO) (Mantua 2007), Arctic Oscillation (AO) (Climate Prediction Center Internet Team 2007) and the North Atlantic Oscillation (NAO) (Jones 2007), and secondary climatic data (potential evapotranspiration (PE)). PE_a values (cm) adjusted to a standard month of 30 days were calculated using Thorthwaite's equation (Thornthwaite 1948):

$$PE_{\mathrm{a}} = 1.6(10T / I)^{a} \qquad [1]$$

where I is a heat index defined as the summation of the 12 monthly values given by $(0.2T)^{1.514}$ when T>0°C, and:

$$a = 6.75\times10^{-7} I^{3} - 7.71\times10^{-5} I^{2} + 1.792\times10^{-3} I + 0.49239 \qquad [2]$$

PE (cm) for a given month is given by:

$$PE = PE_{\mathrm{a}}(h / 12)(N / 30) \qquad [3]$$

where h is mean day length and N is the number of days in the month.

Correlation and response-function analysis was performed on each chronology using ring width as the predictor for mean summer temperatures. Transfer function models using the Churchill temperature data were developed and tested (Fritts 1976) to estimate past summer temperatures from the residual tree-ring chronologies. Regression coefficients were bootstrapped in the statistical software R (R Development Core Team 2006) using 999 iterations over the calibration period and verified using an independent period (Fritts 1991). Summer temperatures were then modeled using a single-variable, least squares linear regression model.

Results

Statistical characteristics of residual chronologies

A total of 220 trees were included in the analyses (Table 3-1), including 8 dead *P. mariana* and 3 dead *P. glauca* within the TUND region and 3 dead *P. mariana* and 2 dead *P. glauca* within the SFOR region. Regardless of species or location, maximum sample depth was during the 1940-1980 period (Fig. 3-2). Preliminary ageing of *L. laricina* indicated that most were too young to yield sufficiently long chronologies so, in light of logistical constraints no *L. laricina* were sampled from the SFOR region. Within the CWMA however, the NFOR *L. laricina* chronology was extended back to 1754 (Fig. 3-2).

Table 3-1: Statistical characteristics of residual chronologies produced for Wapusk National Park and the Churchill Wildlife Management Area

Species:	*Picea glauca*			*Picea mariana*			*Larix laricina*	
Sites:	NFOR[a]	TUND[a]	SFOR[a]	NFOR	TUND	SFOR	NFOR	TUND
Chronology length	1745-2003	1775-2004	1731-2004	1718-2003	1739-2004	1744-2004	1754-2002	1927-2003
Number of years	258	229	273	285	265	260	248	75
Number of trees	77	15	10	32	24	21	39	2
Mean ring width (mm)	0.73	0.59	0.61	0.31	0.39	0.39	0.38	1.03
Mean sensitivity	0.19	0.22	0.20	0.20	0.21	0.20	0.27	0.30
First order autocorrelation	0.67	0.66	0.52	0.57	0.67	0.65	0.27	0.46
Common interval analysis	1900-2000	1900-2000	1900-2000	1900-2000	1900-2000	1900-2000	1900-2000	1970-2000
Number of trees	4	3	5	17	8	10	9	2
Variance in first eigenvector (%)	42.22	40.09	38.58	22.96	24.62	21.15	41.80	66.27
Agreement with population chronology	0.55**	0.78**	0.87**	0.83**	0.82**	0.83**	0.84**	0.85**
Mean correlation among all radii	0.27**	0.31**	0.33**	0.19*	0.20*	0.16	0.37**	0.60**

[a] NFOR = north forest, TUND = central tundra, SFOR = south forest
*Significant at $p<0.10$
**Significant at $p<0.01$

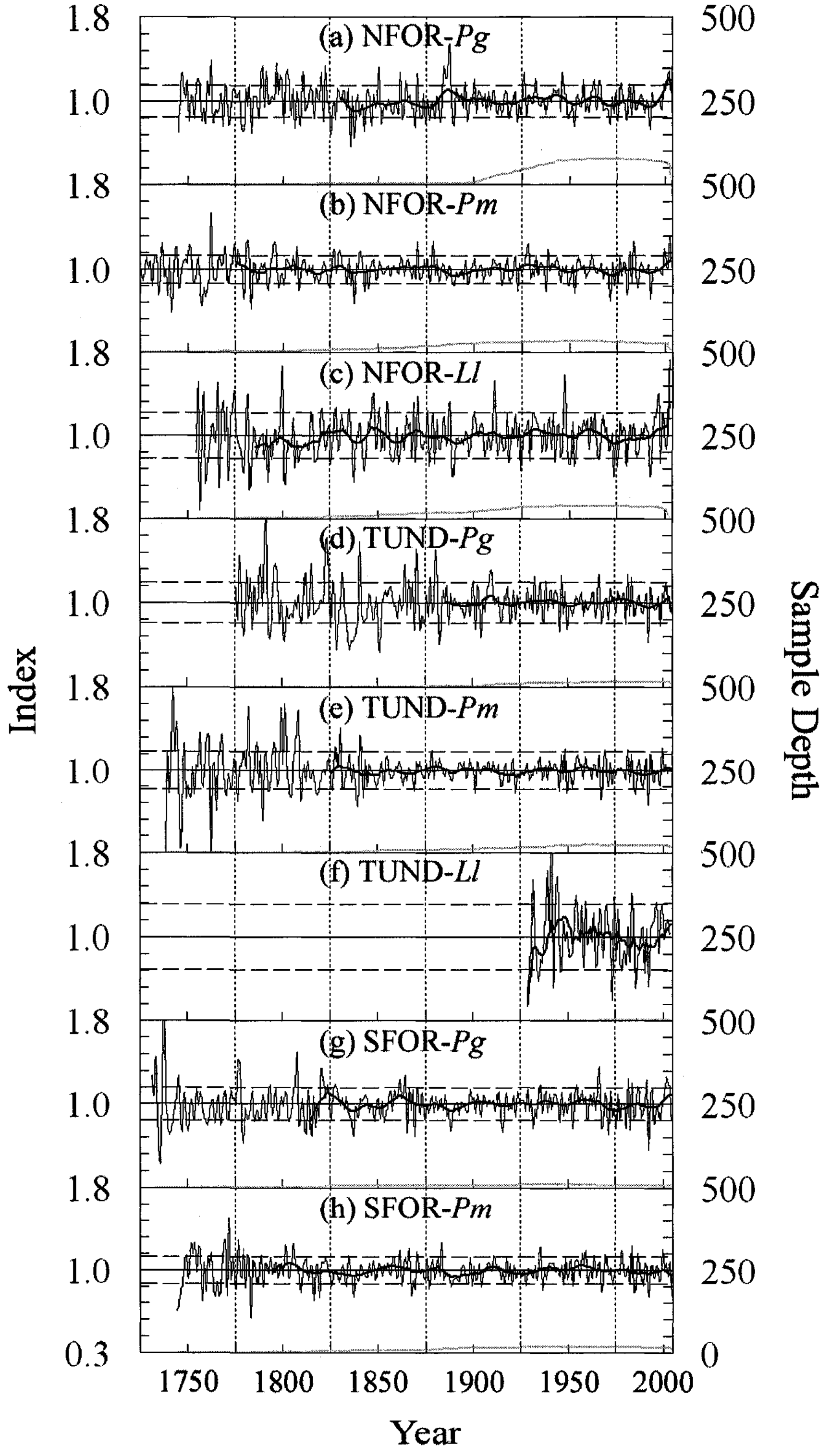


Figure 3-2: Standardized chronologies for each site. (a) NFOR *P. glauca*, (b) NFOR *P. mariana*, (c) NFOR *L. laricina*, (d) TUND *P. glauca*, (e) TUND *P. mariana*, (f) TUND *L. laricina*, (g) SFOR *P. glauca* and (h) SFOR *P. mariana*. The thick grey line is the sample depth for each chronology. The thick black line is a spline that preserves 90% of the variance at wavelengths of 32 years with the exception of the TUND L. laricina index which is an 11-year running mean as there was insufficient sample depth to generate a spline (n=2). Horizontal dashed lines indicate one sigma. The spline was created using the program SIGLOF and requires a minimum sample depth (n=3) and therefore does not extend to the earliest part of the chronology.

Statistical characteristics were similar among all of the sites (Table 3-1). Agreement with the population chronology was equal to or exceeded 0.8 ($p<0.01$) with the exception of NFOR *P. glauca*, which had a low correlation of 0.6 ($p<0.01$). The low correlation was notable considering the variance explained by the first eigenvector of the NFOR *P. glauca* index (42%) was the highest of all the chronologies followed closely by the TUND (40%) and SFOR (39%) *P. glauca* chronologies, indicating a strong environmental forcing common among the *P. glauca* trees of the entire region. The *P. mariana* chronologies had considerably less variation explained by the first eigenvector (values ranged from 21% for the SFOR to 25% for the TUND) (Table 3-1). The *L. laricina* chronologies had a considerable amount of variance explained in the first eigenvector with 42% and 66% explained for the NFOR and TUND chronologies respectively. Additionally the highest sensitivity values were observed in the two *L. laricina* chronologies as was the lowest first order autocorrelation, indicating a high annual variation in ring width and low persistence. Higher sample replication is necessary however in order to confirm the validity of the TUND *L. laricina* statistics ($n=2$) (Fig. 3-2).

Influence of climate on radial growth

Regional climatology:

In order to test for anomalies in analysis due to increasing distance from the climate station in Churchill, the chronologies were compared to climate data from Gillam, approximately 260 km SSW of Churchill, 120 km inland and 10 km closer to the centre of the SFOR sites (Figs. 3-3 & 3-4). The statistics were quite similar to those observed with the Churchill data with some exceptions: NFOR *P. glauca* growth was positively correlated with October temperatures of the previous year (t-1) at Gillam and current year (t) summer temperatures at Churchill (Figs. 3-3(a & d)). NFOR *P. mariana* growth was positively correlated with May (t-1) and October (t-1) Churchill temperatures, and negatively correlated with May (t) temperatures at the same locality. NFOR *L. laricina* growth was positively correlated with September and October (t-1) temperatures at Churchill. TUND *P. glauca* growth was negatively correlated with September and December (t-1) temperatures at Gillam, and July/August (t-1) (negatively) and June/August (t) (positively) temperatures at Churchill (Figs. 3-3(b & e)). TUND *P. mariana* growth was associated with August (t-1) temperatures and TUND *L. laricina* growth positively associated with September (t-1) and spring and autumn (t) temperatures, both at Churchill. SFOR *P. glauca* growth was negatively associated with July/August (t-1) and positively associated with July/summer (t) temperatures at Churchill (Figs. 3-3(c & f)).

Few significant correlations were observed between radial growth and precipitation at Gillam (Fig. 3-4). NFOR *P. glauca* and *P. mariana* growth was positively correlated with December precipitation (t-1) at Gillam, as was SFOR *P. mariana* with March (t). SFOR *P. glauca* growth was negatively associated with October (t-1) precipitation at Gillam. The radial growth/Churchill precipitation associations were not mirrored within the Gillam dataset and will be discussed later (Figs. 3-4(a-c)).

Temperature:

All species across all sites responded positively to Churchill July temperatures and either June, August or a combination of both (summer) of the current year (t) during the 1929-2002 period (all correlations are significant at $p<0.05$) (Figs. 3-

3(a-c)). The exception was the SFOR *P. mariana* chronology, which was not positively correlated with any climatic variable except October temperature of the previous year (t-1). October of the previous year was significantly positively correlated with growth in all species at all sites, while September (t-1) was also positively correlated with growth of *L. laricina* at the NFOR and TUND sites. May temperatures (t-1) were significantly positively correlated with growth only in the NFOR *P. mariana* chronology. The TUND *L. laricina* chronology was significantly positively correlated with spring temperatures (t) (March-May). Conversely, the NFOR *L. laricina* and *P. mariana* chronologies were significantly negatively correlated with current year spring temperatures (t). All TUND and SFOR chronologies were significantly negatively correlated with previous summer temperatures (t-1), with the exception of the TUND *L. laricina* chronology which was not associated (Figs. 3-3(b & c)).

Precipitation:

Precipitation at Churchill was infrequently associated with ring width (Figs. 3-4(a-c)). The NFOR and SFOR *P. glauca* chronologies were negatively associated with August precipitation (t). In addition, the NFOR *L. laricina* and *P. mariana* chronologies were positively associated with March and April precipitation (t), respectively. TUND and SFOR *P. glauca* and *P. mariana* chronologies were negatively correlated with January precipitation (t). The TUND *L. laricina* chronology was correlated with August precipitation of the previous year (t-1).

Potential evapotranspiration:

P. glauca growth within NFOR sites was positively correlated with PE of Jun (t-1) at Churchill, and growth of all three species was negatively correlated with June/July and summer (t) PE values, while *L. laricina* growth was negatively correlated with September (t-1) PE (Fig. 3-5(a-c)). Growth of *P. glauca* and *P. mariana* was positively correlated with PE of the previous year (t-1) within the TUND site, and all three species were negatively correlated with June, July and summer (t) PE (Fig. 3-5(b)). Growth of both TUND *P. glauca* and *L. laricina* was negatively correlated with August (t) PE and *L. laricina* was negatively correlated with September PE of the previous year (t-1). *P. glauca* and *P. mariana* growth within the SFOR site was positively correlated with PE of June and August (t-1), and *P. glauca* was also positively correlated with July (t-1) and negatively correlated with June/July and summer (t) PE (Fig. 3-5(c)).

Snowpack:

The *P. mariana* chronology from the NFOR site was positively correlated with snow on the ground on the last day of the month at Churchill during April and spring (t) (Fig. 3-6(a)). Snow accumulation data was only available back to 1947. As well, *L. laricina* growth within the NFOR site was positively correlated with April (t-1) and negatively correlated with September (t-1) snow on the ground. *L. laricina* growth within the TUND site was similarly negatively correlated with September (t-1) snow on the ground, but positively correlated with the April (t) snowpack depth (Fig. 3-6(b)). No significant correlations were found with the SFOR chronologies (Fig. 3-6(c)).

Wind:

Growth of *P. glauca* within the NFOR site was positively correlated with maximum velocity of wind gust at Churchill in January and July (t) (Fig. 3-6(d)). The TUND *P. mariana* and *L. laricina* chronologies were positively correlated with maximum wind gust velocity during July (t) (Fig. 3-6(e)). The SFOR *P. mariana* chronology was positively correlated with July, summer and autumn (t) maximum wind gust and *P. glauca* growth was positively correlated with annual maximum gusts (Fig. 3-6(f)). Wind gust data date from 1957-1993.

Inter-correlations:

Simple correlations were calculated in order to evaluate the influence of the annular modes and other hemispherical patterns of climate variability on the climate surrounding Churchill (Table 3-2) ($p<0.05$). The NAO was not significantly associated with climate with the exception of positively affecting snow depth in September and exhibiting a negative effect in November. The AO was positively associated with temperature in August and October, negatively affected maximum wind gust velocity during summer and negatively affected snow depth in April. The PDO was positively associated with temperature during January/February and winter, and negatively associated during autumn. Additionally, the PDO was positively associated with precipitation in January and negatively during November, and was negatively associated with maximum wind gust velocity during August and summer. The ENSO was positively correlated with temperature during January/March and negatively during November, and was positively associated with precipitation in September and winter. The ENSO was negatively associated with maximum wind gust velocity during January, April and October, and was positively associated during May. In addition, temperature and precipitation were positively associated only during the winter months (Table 3-2).

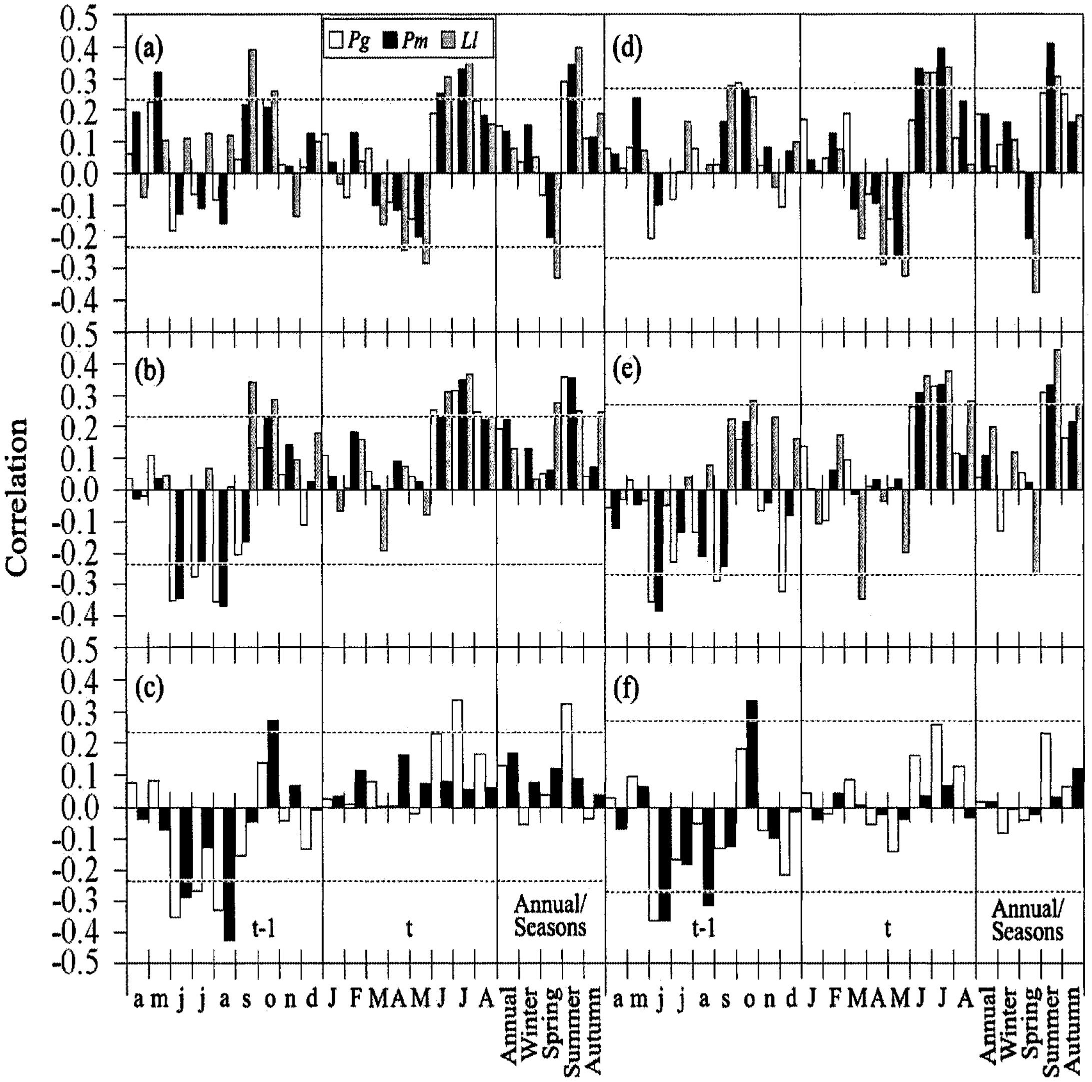


Figure 3-3: Correlation between mean monthly temperature at: (a),(b),(c) Churchill ((d),(e),(f) Gillam), and the residual chronologies from each site for the 1929-2002 (1943-2002) period. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). (a & d) NFOR, (b & e) TUND, and (c & f) SFOR. Correlations were also computed seasonally, where the annual values are taken as the mean of September of the year preceding growth (t-1) to August of the current year growth (t); winter values include December of year t-1 to February of year t; autumn values include September to November of the year t-1; and summer consists of June through August of year t. Correlation coefficients of magnitude greater than ±0.23 (±0.27) (horizontal dashed lines) are significant at $p < 0.05$.

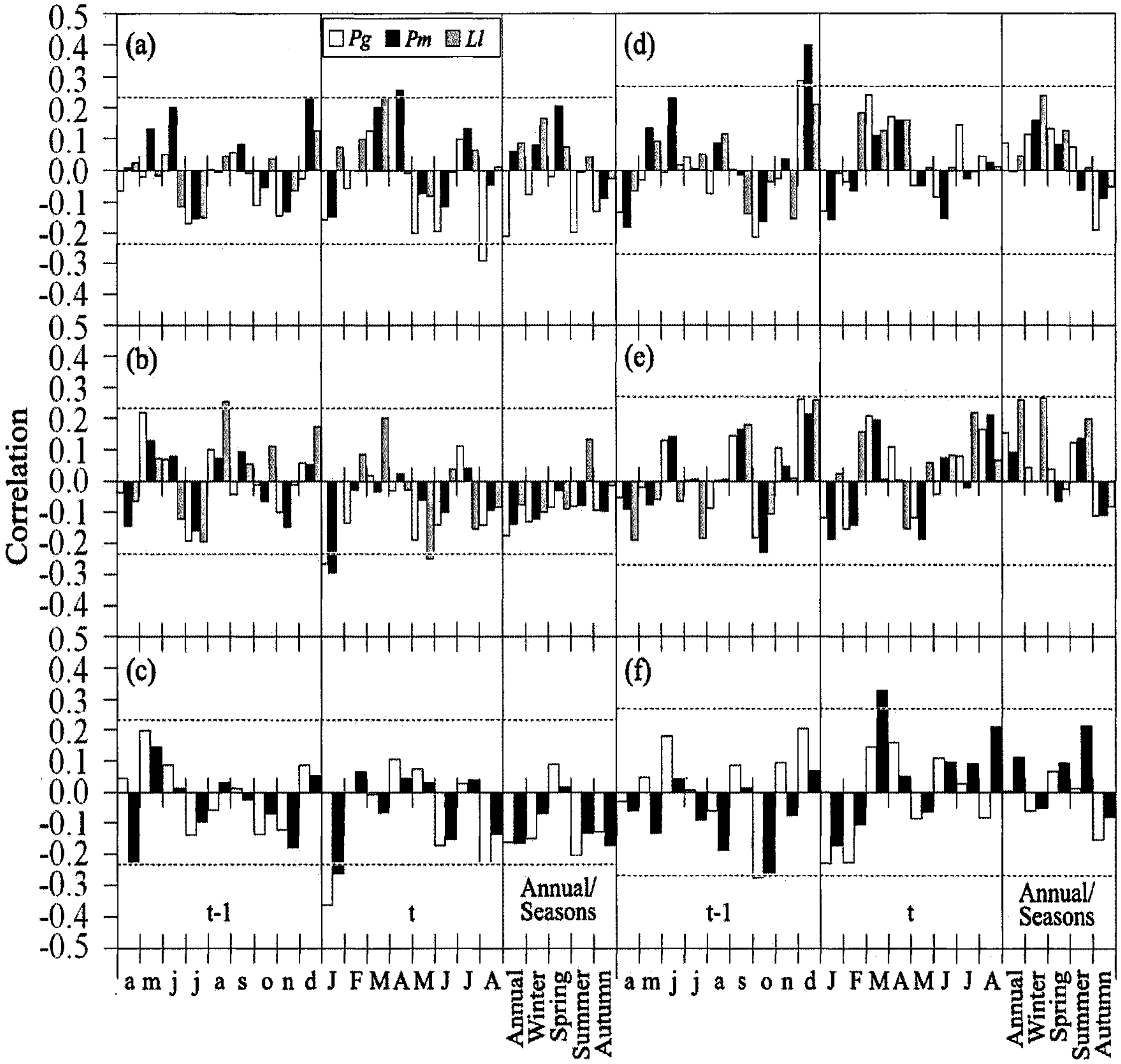


Figure 3-4: Correlation between the sum of monthly precipitation at: (a),(b),(c) Churchill ((d),(e),(f) Gillam) and the residual chronologies from each site for the 1932-2002 (1943-2002) period. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). (a & d) NFOR, (b & e) TUND, and (c & f) SFOR. Correlations were also computed seasonally where the annual values are taken as the sum of September of the year preceding growth (t-1) to August of the current year growth (t); winter values include December of year t-1 to February of year t; autumn values include September to November of the year t-1; and summer consists of June through August of year t. Correlation coefficients of magnitude greater than ±0.23 (±0.27) (horizontal dashed lines) are significant at $p < 0.05$.

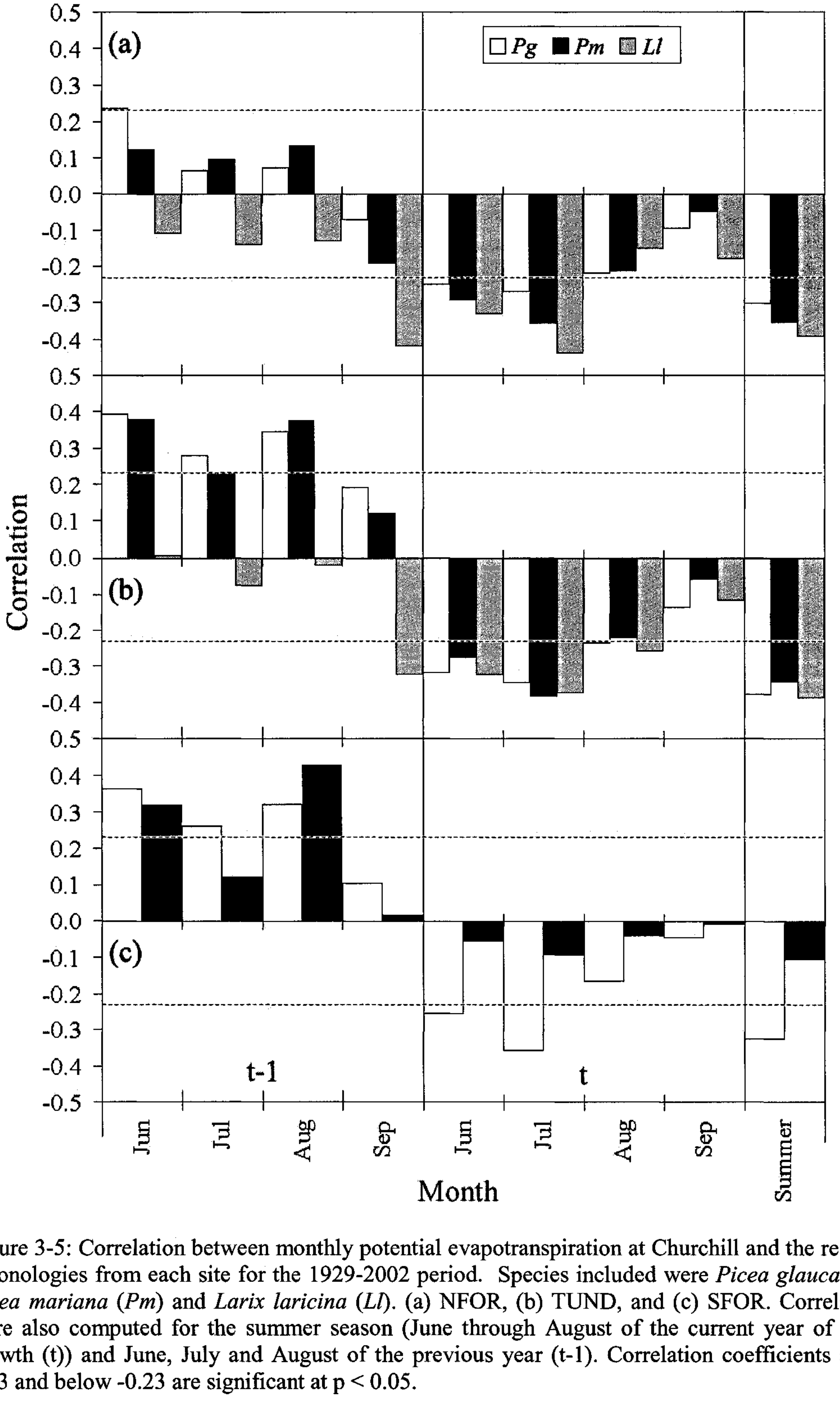


Figure 3-5: Correlation between monthly potential evapotranspiration at Churchill and the residual chronologies from each site for the 1929-2002 period. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). (a) NFOR, (b) TUND, and (c) SFOR. Correlations were also computed for the summer season (June through August of the current year of radial growth (t)) and June, July and August of the previous year (t-1). Correlation coefficients above 0.23 and below -0.23 are significant at $p < 0.05$.

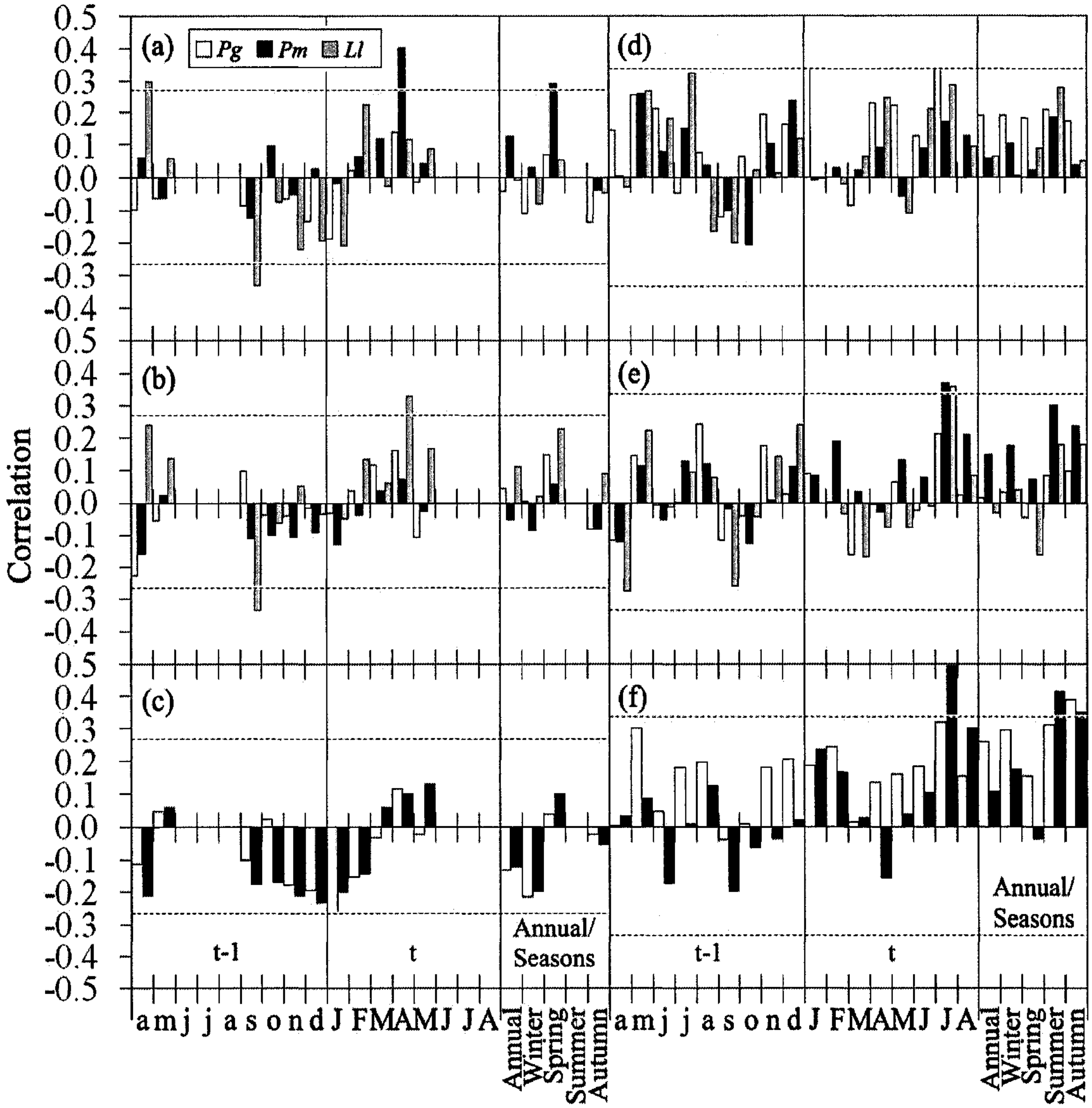


Figure 3-6: Correlation between (a),(b),(c) depth of snow on the ground on the last day of the month and ((d),(e),(f) velocity of maximum wind gust) at Churchill, and the residual chronologies from each site for the 1947-1999 (1957-1993) period. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). (a & d) NFOR, (b & e) TUND, and (c & f) SFOR. Correlations were also computed seasonally where the annual values are taken as the mean of September of the year preceding growth (t-1) to August of the current year growth (t); winter values include December of year t-1 to February of year t; autumn values include September to November of the year t-1; and summer consists of June through August of year t. Correlation coefficients of magnitude greater than ±0.27 (±0.33) (horizontal dashed lines) are significant at $p < 0.05$.

Table 3-2: Correlation between climate at Churchill and hemispheric patterns of climate variability

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Win	Spr	Sum	Aut
Temperature																	
NAO	0.12	-0.03	-0.09	-0.13	0.02	0.02	0.05	0.09	-0.02	-0.14	-0.09	-0.11	0.05	0.00	-0.12	0.03	-0.03
AO	-0.03	-0.03	-0.10	0.00	0.03	0.24	0.25	**0.51**	0.02	**0.34**	-0.06	-0.15	-0.19	-0.11	0.14	0.14	-0.03
PDO	**0.24****	**0.31**	0.12	0.01	-0.15	-0.07	0.13	-0.17	-0.16	-0.14	-0.19	0.16	0.20	**0.30**	0.03	-0.01	**-0.24**
ENSO	**0.28**	0.08	**0.33**	0.08	-0.17	-0.05	-0.11	-0.10	-0.12	-0.15	**-0.32**	0.13	0.11	0.24	0.11	-0.10	-0.09
Precipitation																	
NAO	0.02	-0.09	0.14	-0.01	0.02	-0.18	-0.12	-0.16	0.14	-0.02	-0.10	-0.05	0.00	0.05	0.07	-0.08	0.12
AO	-0.04	-0.04	0.01	-0.22	-0.16	-0.06	-0.08	0.08	-0.10	-0.09	-0.09	0.13	-0.04	0.03	-0.02	0.08	-0.08
PDO	**0.30**	0.19	0.21	-0.01	-0.02	**-0.24**	-0.09	0.07	0.09	0.03	**-0.38**	0.06	0.02	0.28	0.12	-0.11	-0.02
ENSO	0.18	0.13	0.04	0.09	0.15	-0.06	0.17	0.02	**0.32**	0.00	-0.22	0.19	0.18	**0.31**	0.13	0.10	0.00
Maximum wind gust velocity																	
NAO	0.13	-0.15	0.17	-0.19	0.23	0.25	-0.26	-0.20	0.23	0.13	-0.02	-0.22	0.01	-0.06	-0.04	-0.01	0.09
AO	0.03	0.09	0.31	-0.02	-0.09	0.23	-0.25	-0.26	-0.32	-0.10	-0.22	-0.27	-0.27	0.03	0.01	**-0.47**	-0.17
PDO	-0.10	0.05	0.12	0.00	-0.15	-0.19	-0.09	**-0.34**	0.05	-0.12	-0.22	0.13	-0.09	0.07	-0.10	**-0.33**	-0.01
ENSO	**-0.58**	0.16	-0.14	**-0.43**	**0.34**	-0.10	-0.26	-0.18	-0.03	**-0.38**	-0.18	-0.22	-0.30	-0.26	-0.25	-0.24	-0.27
Snow depth																	
NAO	0.00	-0.03	0.18	-0.09	-0.09	0.00	0.00	0.00	**0.37**	0.08	**-0.34**	0.08	0.01	0.02	-0.16	0.00	-0.09
AO	-0.07	0.04	0.01	**-0.29**	-0.27	0.00	0.00	0.00	-0.10	-0.09	-0.05	-0.08	-0.09	-0.07	-0.13	0.00	-0.10
PDO	-0.04	-0.01	-0.25	0.05	0.08	0.00	0.00	0.00	-0.01	-0.03	-0.17	-0.01	-0.08	-0.03	-0.07	0.00	-0.20
ENSO	-0.17	-0.21	-0.20	0.06	0.20	0.00	0.00	0.00	0.15	-0.04	-0.18	-0.16	-0.12	-0.22	-0.07	0.00	-0.17
Temperature/Precipitation																	
	0.29	**0.40**	0.15	0.10	0.08	-0.05	-0.01	-0.14	-0.05	-0.17	0.14	**0.28**	-0.02	**0.40**	0.02	-0.03	0.04

*Correlations in bold, underlined print are significant at p<0.05.

Hemispheric climate variability and radial growth

Growth of *P. mariana* within the NFOR site was positively correlated with the NAO during January (t) (Fig. 3-7(a)). The TUND *L. laricina* chronology was negatively correlated with the NAO May, August and summer (t) (Fig. 3-7(b)). No significant correlations were observed between radial growth in the SFOR sites and the NAO (Fig. 3-7(c)). *L. laricina* growth within the NFOR sites was negatively correlated with the July and December (t-1) AO (Fig. 3-7(d)). The TUND *L. laricina* chronology was positively correlated with the AO during July (t) and the *P. mariana* chronology was negatively correlated with the AO during August and summer (t) (Fig. 3-7(e)). Within the SFOR site, *P. glauca* growth was negatively correlated with the July (t-1) AO and *P. mariana* negatively correlated with the AO during February and summer (t) (Fig. 3-7(f)). Growth of *P. glauca* within the NFOR and TUND sites was positively correlated with ENSO during August (t), and NFOR *P. glauca* growth was also positively correlated with ENSO during summer (t) (Figs. 3-8(a & b)). Additionally, a cyclical character was present in the ENSO correlation functions in that primarily negative correlations during spring of the previous year (t-1) to the end of spring of the current year (t), turned to positive correlations during the summer (t) (Figs. 3-8(a-c)). All three species within the NFOR site were negatively correlated with the PDO during November (t-1) (Fig. 3-8(d)). No other significant associations with PDO were observed among the chronologies (Figs. 3-8(e& f)).

Changes in radial growth response to climate

Growth of *P. glauca* within the NFOR region was not associated with summer temperatures (Fig. 3-9(a)). Growth of *P. mariana* and *L. laricina* within the same region however, was associated with summer temperatures except for a period from the late-1950s through to the late-1970s (Fig. 3-9(a)). Radial growth of *P. glauca* and *P. mariana* within the TUND region was associated with summer temperatures from the start of the comparison to the late-1950s and for a short period during the 1980s (*P. glauca*) and the end of the comparison (*P. mariana*) (Fig. 3-9(b)). *L. laricina* growth within the TUND region was associated with summer temperatures from the early-1950s onward. Within the SFOR region, *P. glauca* growth was associated with summer temperatures from the 1970s onward while growth of *P. mariana* was not associated (Fig. 3-9(c)). Compared to the early portion of the comparison, chronologies at all three locales generally had lower correlations with temperature in recent decades.

All chronologies were associated with the NAO primarily during the late-1800s and early 1900s, with the exception of *L. laricina* within the NFOR and *P. mariana* within the SFOR which were not correlated (Fig. 3-9(d-f)). There was also a marked decrease in correlations post-1900 among all chronologies except the SFOR *P. mariana*. All chronologies had little to no association with the AO with the exception of *P. mariana* within the SFOR, which was negatively correlated most of the time (Fig. 3-9(g-i)).

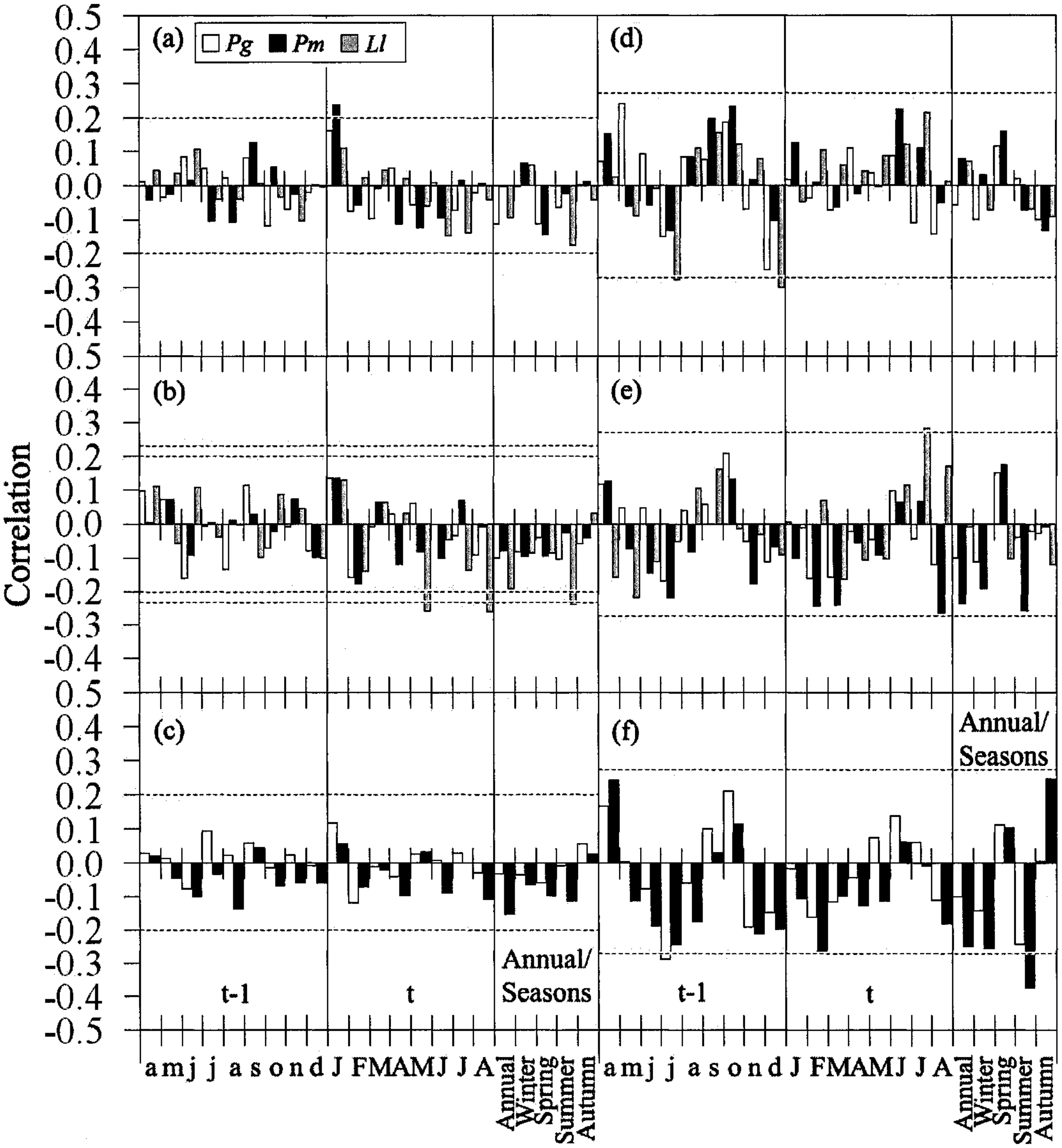


Figure 3-7: Correlation between the (a),(b),(c) North Atlantic Oscillation index (NAO) ((d),(e),(f) Arctic Oscillation (AO)) and the residual chronologies from each site for the 1821-2002 (1950-2002) period. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). (a),(d) NFOR, (b),(e) TUND, and (c),(f) SFOR. Correlations were also computed seasonally where the annual values are taken as the mean of September of the year preceding growth (t-1) to August of the current year growth (t); winter values include December of year t-1 to February of year t; autumn values include September to November of the year t-1; and summer consists of June through August of year t. Correlation coefficients of magnitude greater than ±0.20 (±0.27) are significant at $p < 0.05$ for all species in all sites with the exception of the NAO/TUND-*L. laricina* correlation (critical r=±0.23) due to lower degrees of freedom (df=74 for TUND *L. laricina* and >100 for the others).

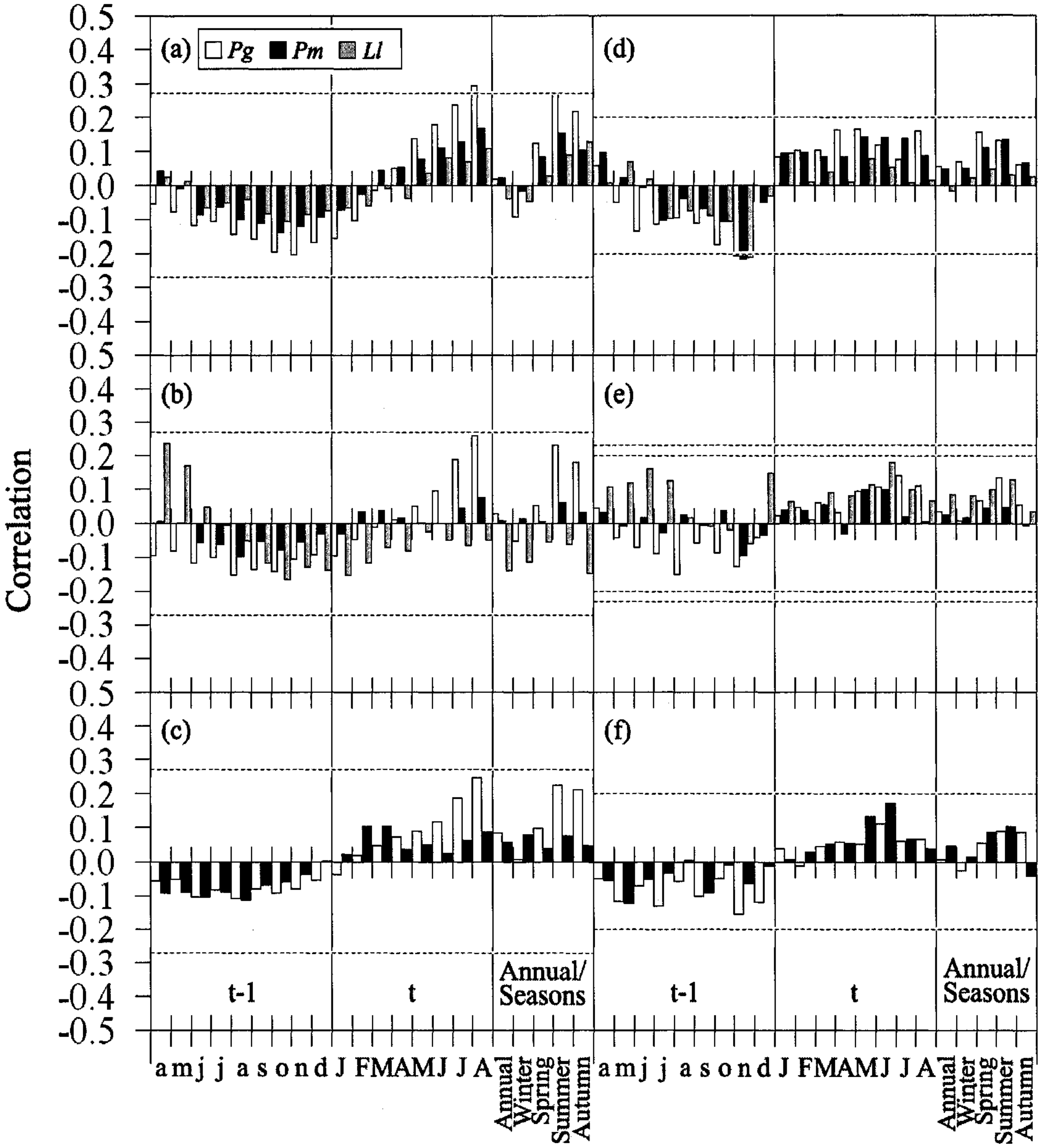


Figure 3-8: Correlation between the (a),(b),(c) El Niño Southern Oscillation index (ENSO) ((d),(e),(f) Pacific Decadal Oscillation (PDO)), and the residual chronologies from each site for the 1950-2002 (1900-2002) period. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). (a),(c) NFOR, (b),(e) TUND, and (c),(f) SFOR. Correlations were also computed seasonally where the annual values are taken as the mean of September of the year preceding growth (t-1) to August of the current year growth (t); winter values include December of year t-1 to February of year t; autumn values include September to November of the year t-1; and summer consists of June through August of year t. Correlation coefficients of magnitude greater than ±0.27 (±0.20) are significant at $p < 0.05$ for all species in all sites with the exception of the PDO/TUND-*L. laricina* chronology (critical r=±0.23) due to lower degrees of freedom (df=76 for TUND *L. laricina* and >100 for the others).

All three *P. glauca* chronologies (NFOR, TUND and SFOR) had some association with ENSO from the early 1960s to the late 1970s (Fig. 3-10(a-c)). The remaining chronologies were not correlated with ENSO. The NFOR *P.*

glauca and *P. mariana* chronologies were associated with the PDO during the 1960 to 1985 period (Fig, 3-10(d-f)). The TUND *L. laricina* chronology was associated with the PDO during the mid-to-late-1940s, as was the SFOR *P. mariana* chronology in the mid-to-late-1910s. The remaining chronologies were little correlated with the PDO. As well, there was a noticeable decline in correlations following the 1950s.

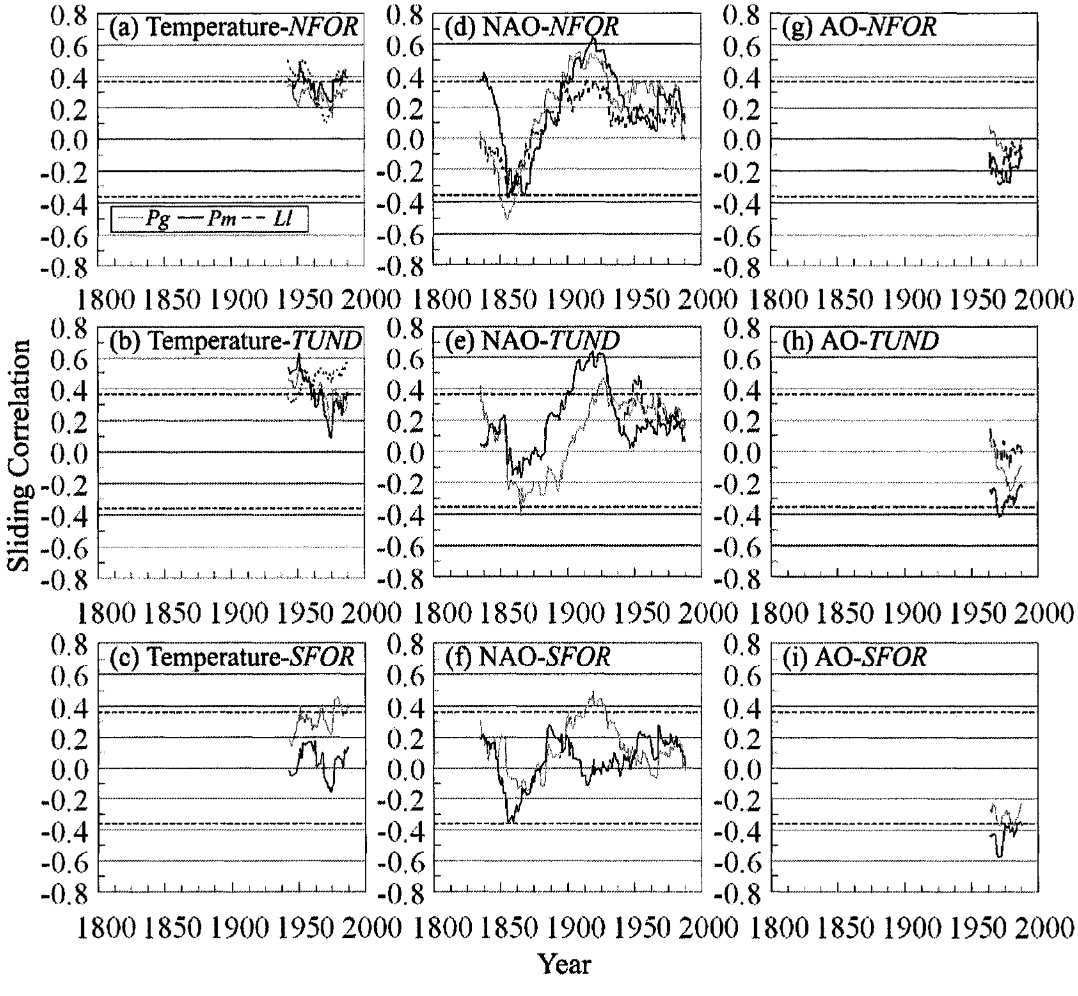


Figure 3-9: Correlations calculated within a 30-year sliding window, between the residual chronologies for each species (*Picea glauca*, (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*)), and climate. (a),(b),(c) Mean summer temperatures at Churchill (1929-2002), (d),(e),(f) the North Atlantic Oscillation (NAO) (1826-2002) during January, and (g),(h),(i) the Arctic Oscillation (AO) (1950-2002) during summer. The horizontal dashed lines indicate the $p<0.05$ significance levels (r±0.36).

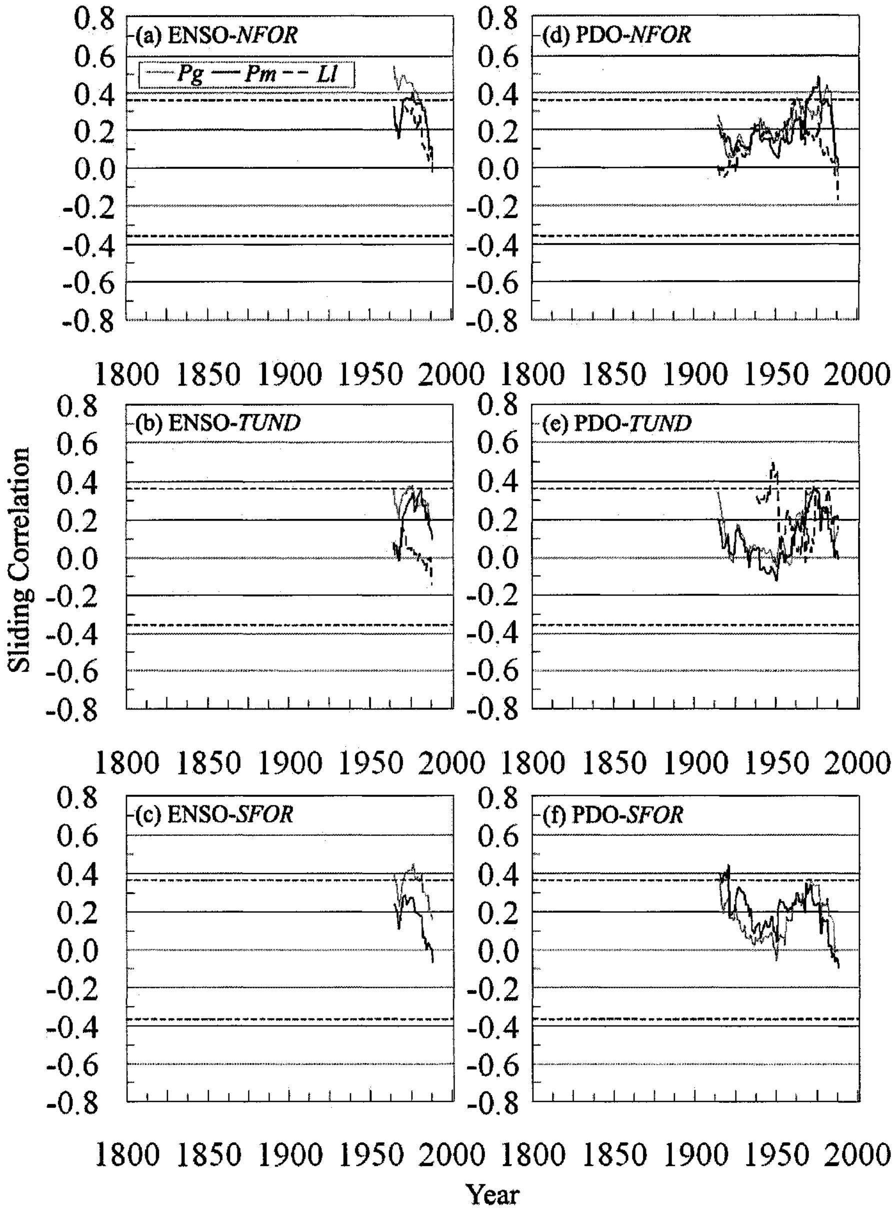


Figure 3-10: Correlations calculated within a 30-year sliding window, between the residual chronologies for each species (*Picea glauca*, (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*)) and two annular modes during summer. (a),(b),(c) El Niño Southern Oscillation (ENSO) (1950-2002) and (d),(e),(f) the Pacific Decadal Oscillation (PDO) (1900-2002). The horizontal dashed lines indicate the $p<0.05$ significance levels (r±0.36).

Single variable, least-squares linear regression

The majority of the chronologies were calibrated using the early portion of the summer temperature record, when the greatest correlations with summer temperatures were occurred (Table 3-3; Fig. 3-9(a-c)). Those regressions with the highest calibration Pearson correlation coefficients were used in the analysis (Fig. 3-11).

Of the NFOR transfer functions, only the *P. mariana* regression passed the calibration (1938-1967) and verification (1968-1997) tests with significant Pearson correlation coefficients (r) and positive reduction of error (RE) coefficients (Fritts 1976) and coefficients of efficiency (CE) (Briffa et al. 1988) (Table 3-3; Fig. 3-11(a-c)). Despite a significant correlation coefficient for the calibration period (1929-1958) as well as for the entirety of the comparison, the NFOR *L. laricina* regression did not pass verification (Fig. 3-11(c)). Failure of all the NFOR regressions of the sign test indicates notable skill for characterizing low- as opposed to high-frequency variation (D'Arrigo and Jacoby 1992). Compared to the other two locales, increases in the NFOR regressions were qualitatively consistent with temperature increases in recent years, particularly the *L. laricina* reconstruction (Fig. 3-11(c)).

Table 3-3: Calibration and verification statistics for temperature reconstructions

Model	Calibration period	Calibration r	r^2 (adj)	Verification period	Verification r	RE	CE	Sign test (+/-)
NFOR-*Picea glauca*								
Early	1930-1959	0.35	0.09	1960-1989	0.17	0.01	-0.05	12/18 (fail)
Late	1960-1989	0.17	0.00	1930-1959	0.35	0.11	0.04	18/12 (fail)
Full	1929-2002	0.28	0.07	-	-	-	-	-
	Model:							
	1930-1959	Summer T=3.495[index]+6.458						
	1960-1989	Summer T=1.531[index]+8.234						
	1929-2002	Summer T=2.925[index]+7.099						
NFOR-*Picea mariana*								
Early	1938-1967	0.49**	0.21	1968-1997	0.37*	0.08	0.08	16/14 (fail)
Late	1968-1997	0.37*	0.11	1938-1967	0.49**	0.19	0.19	21/9 (pass)
Full	1929-2002	0.36	0.12	-	-	-	-	-
	Model:							
	1938-1967	Summer T=6.135[index]+3.724						
	1968-1997	Summer T=4.232[index]+5.818						
	1929-2002	Summer T=3.995[index]+6.056						
NFOR-*Larix laricina*								
Early	1929-1958	0.49**	0.21	1959-1988	0.15	0.00	-0.08	17/13 (fail)
Late	1959-1988	0.15	-0.01	1929-1958	0.49**	0.15	0.09	20/9 (pass)
Full	1929-2002	0.40*	0.15	-	-	-	-	-
	Model:							
	1929-1958	Summer T=2.920[index]+7.010						
	1959-1988	Summer T=1.021[index]+8.716						
	1929-2002	Summer T=2.518[index]+7.506						

r	Pearson correlation coefficient
RE	Reduction of error statistic (positive values are considered a pass of the verification test)
CE	Coefficient of efficiency (positive values are considered a pass of the verification test)

*Significant at $p<0.05$

**Significant at $p<0.01$

Table 3-3: Continued

Model	Calibration period	Calibration r	r^2 (adj)	Verification period	Verification r	RE	CE	Sign test (+/-)
TUND-*Picea glauca*								
Early	1938-1967	0.55**	0.28	1968-1997	0.35	0.12	0.12	17/13 (fail)
Late	1968-1997	0.35	0.09	1938-1967	0.55**	0.29	0.29	20/10 (pass)
Full	1929-2002	0.35	0.11	-	-	-	-	-
	Model:							
	1938-1967	Summer T=4.544[index]+5.365						
	1968-1997	Summer T=3.794[index]+6.180						
	1929-2002	Summer T=3.282[index]+6.769						
TUND-*Picea mariana*								
Early	1937-1966	0.62**	0.37	1967-1996	0.27	-0.11	-0.11	15/15 (fail)
Late	1967-1996	0.27	0.04	1937-1966	0.62**	0.25	0.25	24/6 (pass)
Full	1929-2002	0.36*	0.12	-	-	-	-	-
	Model:							
	1937-1966	Summer T=6.630[index]+3.226						
	1967-1996	Summer T=2.718[index]+7.271						
	1929-2002	Summer T=3.837[index]+6.231						
TUND-*Larix laricina*								
Early	1943-1972	0.50**	0.23	1973-2002	0.57**	0.41	0.33	21/9 (pass)
Late	1973-2002	0.57**	0.30	1943-1972	0.50**	0.40	0.25	22/8 (pass)
Full	1929-2002	0.41*	0.16	-	-	-	-	-
	Model:							
	1943-1972	Summer T=3.126[index]+7.243						
	1973-2002	Summer T=2.456[index]+7.220						
	1929-2002	Summer T=1.717[index]+8.306						

r	Pearson correlation coefficient
RE	Reduction of error statistic (positive values are considered a pass of the verification test)
CE	Coefficient of efficiency (positive values are considered a pass of the verification test)

*Significant at $p<0.05$

**Significant at $p<0.01$

Table 3-3: Continued

Model	Calibration period	Calibration r	r^2 (adj)	Verification period	Verification r	RE	CE	Sign test (+/-)
SFOR-*Picea glauca*								
Early	1935-1964	0.29	0.05	1965-1994	0.47**	0.22	0.22	15/15 (fail)
Late	1965-1994	0.47**	0.19	1935-1964	0.29	0.09	0.09	20/10 (pass)
Full	1929-2002	0.30	0.07	-	-	-	-	-
	Model:							
	1935-1964	Summer T=3.400[index]+6.529						
	1965-1994	Summer T=3.039[index]+6.827						
	1929-2002	Summer T=2.462[index]+7.602						
SFOR-*Picea mariana*								
Early	1948-1977	0.17	0.00	1978-2002	0.12	0.00	-0.12	17/13 (fail)
Late	1978-2002	0.12	-0.03	1948-1977	0.17	0.00	-0.26	18/12 (fail)
Full	1929-2002	0.05	-0.01	-	-	-	-	-
	Model:							
	1948-1977	Summer T=1.823[index]+8.009						
	1978-2002	Summer T=1.528[index]+8.819						
	1929-2002	Summer T=0.555[index]+9.494						

r	Pearson correlation coefficient
RE	Reduction of error statistic (positive values are considered a pass of the verification test)
CE	Coefficient of efficiency (positive values are considered a pass of the verification test)

*Significant at $p<0.05$

**Significant at $p<0.01$

The *L. laricina* transfer function was the only regression from the TUND chronologies to pass both calibration (1973-2002) and verification (1943-1972), as well as all other tests indicating substantial predictive skill in the reconstruction (Table 3-3; Fig. 3-11(h)). Although the TUND *P. glauca* regression passed calibration (1938-1967), it did not pass verification (1968-1997) but did pass the RE and CE tests, indicating some predictive skill in the reconstructions (Fig. 3-11(b)). Similarly the TUND *P. mariana* regression passed calibration (1937-1966) and was highly correlated with temperature over the complete record (1929-2002), but failed all other tests (Table 3-3; Fig. 3-11(e)). The SFOR *P. glauca* regression passed calibration (1965-1994) as well as the sign test, RE and CE tests, but failed verification (1935-1964) (Table 3-3; Fig. 3-11(c)). The SFOR

P. mariana regression failed all calibration and verification tests and was therefore not useful in reconstructing summer temperatures (Fig. 3-11(f)).

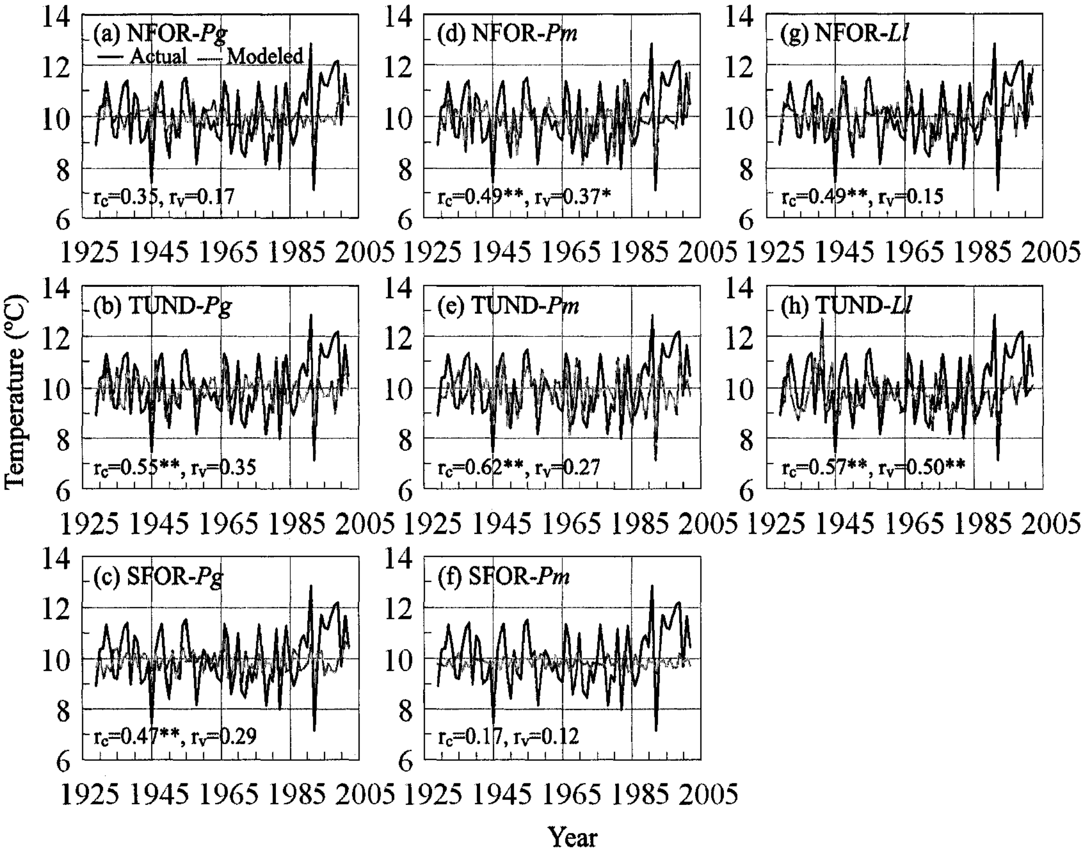


Figure 3-11: Actual (black) and the modeled (grey) summer temperatures (June-August) based on the residual chronologies at each site and climatic data for the Churchill area from 1929-2002. (a),(d),(g) NFOR, (b),(e),(h) TUND and (c),(f) SFOR. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). Pearson correlation coefficients for the calibration (r_c) and verification (r_v) periods are shown (*p<0.05 and **p<0.01 significance).

Inter-species / inter-site correlations

The NFOR chronologies were significantly correlated with each other for most of the comparison, as were the SFOR chronologies (Fig 3-12(a)) (all correlations stated were significant at $p<0.05$). The TUND *P. glauca* and *P. mariana* chronologies were significantly correlated during the 20th century, but uncorrelated prior to that. The TUND *P. glauca* and *P. mariana* chronologies were significantly correlated with the TUND *L. laricina* index only during the late 1970s.

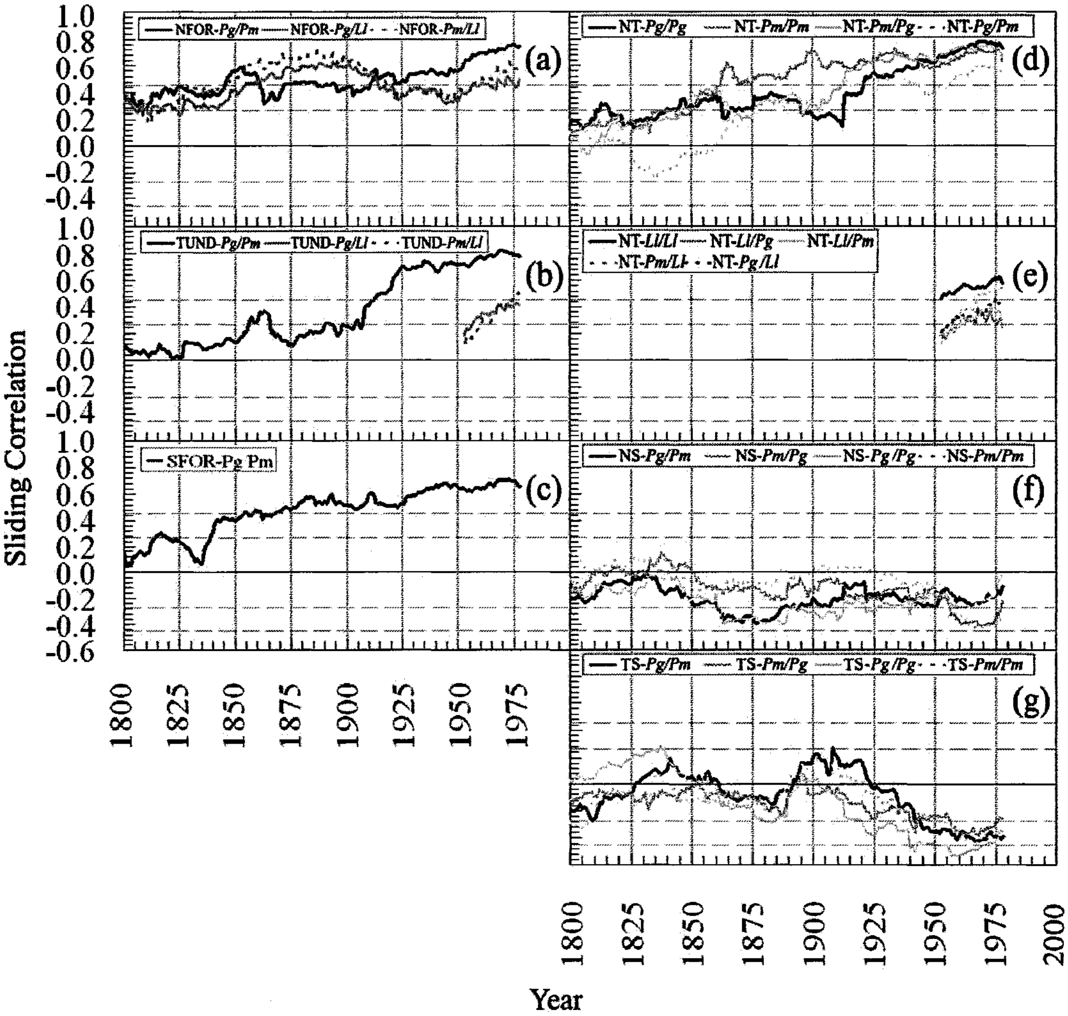


Figure 3-12: Inter-site correlations between the residual chronologies, calculated within a 50-year sliding window. Species included were *Picea glauca* (*Pg*), *Picea mariana* (*Pm*) and *Larix laricina* (*Ll*). (a) Correlations between the NFOR chronologies; (b) same analysis for the TUND chronologies and; (c) correlation analysis conducted between the SFOR chronologies. Intra-site correlations: (d),(e) between the NFOR and TUND chronologies (e.g., NT-*Pg*/*Pm* denotes the correlation between *P. glauca* within the NFOR site correlated with *P. mariana* within the TUND site); (f) same analysis for the NFOR and SFOR chronologies and; (g) correlation analysis conducted between the TUND and SFOR chronologies. The dashed lines indicate the p<0.001 and p<0.05 significance levels.

All NFOR and TUND *Picea* chronologies were significantly correlated for most of the comparison from the late 1830s onward and uncorrelated prior to that, with the exception of the NFOR *P. glauca*/TUND *P. mariana* comparison in which they were uncorrelated prior to the 1870s (Fig. 3-12(d)). The remainder of the NFOR and TUND chronologies were significantly correlated with each other after the 1950s, except the NFOR and TUND *L. laricina* chronologies which were significantly correlated during the entire comparison (Fig. 3-12(e)). The NFOR *P. glauca* chronology was significantly negatively correlated with the SFOR *P. mariana* and *P. glauca* chronologies from the 1860s to the mid-1880s and early 1910s, respectively, and uncorrelated for the remainder of the comparison (Fig. 3-12(f)). The NFOR *P. mariana* chronology was significantly negatively correlated with both SFOR chronologies from the late 1950s onward and uncorrelated otherwise. All TUND and SFOR chronologies were significantly negatively correlated from the late 1950s onward (and primarily uncorrelated otherwise), with the exception of the TUND *P. glauca* compared to the SFOR *P. mariana* and *P. glauca* chronologies, with which the negative correlation persisted from the early 1940s and early 1920s, respectively (Fig. 3-12(g)).

Discussion

Synoptic climate

Numerous occurrences of growth above and below one standard deviation were observed in the chronologies (Fig. 3-2). Growth above one standard deviation was interpreted as enhanced growth and below as suppressed growth. Suppressed growth for all species was recorded in 1992, the year following the eruption of Mount Pinatubo, when a decrease of 0.5°C occurred in global temperatures (Kelly et al. 1996; Parker et al. 1996), and July and summer (June-August) temperatures at Churchill were reduced by 4.3 and 2.6°C (relative to the

1961-1990 mean), respectively (Fig. 3-2). Numerous cold years such as 1792, 1816, and 1888 correspond to years following other major volcanic eruptions that caused global cooling (Kelly et al. 1996; Mass and Portman 1989; Parker et al. 1996) and tree growth suppression (D'Arrigo and Jacoby 1999). A cold period occurring around 1837 has been attributed to a southward migration of the Arctic front (Girardin et al. 2005; Hofgaard et al. 1999; Scott et al. 1988), potentially related to volcanic forcing (D'Arrigo and Jacoby 1999). The correlation and response function analyses emphasized the importance of summer temperatures on radial growth within the NFOR and TUND sites, with a weaker response in the SFOR sites. Furthermore, the minute differences between SFOR tree growth and Gillam/Churchill climate data suggest the decrease in growth response was not an artifact of increasing distance from the source of the climate data in Churchill.

Regional climate

Similar temperature relations were found by Girardin et al. (2005) and D’Arrigo and Jacoby (1993) within the Churchill area and by Briffa et al. (2002) for eastern Canada. The correlation with autumn temperatures has been found to be important in affecting tree growth in the Hudson Bay Lowlands (Girardin et al. 2005; Jacoby and Ulan 1982), due to increased late-season photosynthesis resulting in greater reserves of carbohydrates for the following year (Garfinkel and Brubaker 1980). The negative association with January precipitation of the current year has been linked to enhanced winter snowfall causing a delayed snowmelt which postponed spring dormancy release and initiation of growth (Vaganov et al. 1999) due to the insulating effects of the snowpack (Kershaw and

McCulloch 2007). This relationship has been observed in other northern tree ring studies (Briffa et al. 2002). The negative association of radial growth with May temperature is likely a consequence of a combination of early snowmelt leading to reduced percolation and increased runoff, and onset of the growing season when the roots of trees are still encased in frozen soil while air temperatures are above zero (Girardin and Tardif 2005; Scott et al. 1993; DeLucia 1986). However, this relationship was not revealed through the correlation analysis with snow depth on the last day of the month in Churchill, which could be related to a lack of temporal resolution in the data, as the snow depth on the last day of the month is not always an indicator of snow conditions throughout the month.

The positive correlations of radial growth with wind are likely related to a number of factors. The basal diameter required for stability of trees affected by wind increases exponentially with height (McMahon 1973). Thus in order to maintain the mechanical stability of tall trees (e.g., maintain uniform stress along the height of the tree (c.f. Dean and Long 1986)), an increase in height requires increased investment of resources into radial growth, which occurs at the expense of height growth (Meng et al. 2006). As well, Nicoll and Ray (1996) found that trees continuously alter their morphology in response to varying wind exposure. The strongest correlations with wind gusts were found during July of the current year (Fig. 6(d-f)). July was the warmest and third wettest month with mean temperature of 12.0°C and sum of precipitation of 56mm. A wetter rooting zone and near-maximum thaw layer (Camill and Clark 1998) would offer the least resistance to root ball shifting under strong winds, resulting in tilted trees and reaction wood. Thus the amount (wider rings) and type (stronger, denser reaction wood) of wood laid down along the stem can be affected by wind (Meng et al. 2006).

Hudson Bay and its seasonal ice cover play a significant role in affecting the climate of the region (Gagnon and Gough 2005; Gough et al. 2004; Rouse 1973). As Hudson Bay is presently ice-free for as little as one month out of the year (August), the persisting high-albedo ice pack allows cold air masses to penetrate into mid-to-southern Canada, resulting in the Subarctic conditions that dominate tree growth in the Hudson Bay lowlands (Ball 1986; Bryson 1966; Rouse 1991). The counter-clockwise circulation within the Bay serves to bring cold ocean currents from Foxe Basin and Hudson Strait southward along the western shore of the Bay (Danielson 1969). This circulation results in a period of ice cover that is 6 weeks longer and surface waters that are 5°C colder than in other parts of the Bay. As well, a relationship has been suggested between the duration of ice cover and climatological oscillations such as the ENSO and NAO (Gough et al. 2004). Gough (2004) determined that breakup of the sea ice occurs later during years of low ENSO (<0 and therefore wet) and strong westerly NAO (>0), and this could potentially be related to a thickening of the ice pack through the counter-clockwise circulation in Hudson Bay compacting the ice to the southwest, near the Hudson Bay lowlands (although Gough noted a potential confounding influence of the 1991 Pinatubo eruption). A later breakup date on the bay means that there is less time for an ice-free water body (lower albedo) to absorb solar radiation and cooling would result (Gagnon and Gough 2005). However, the

October-April period is predicted to warm the greatest in the Arctic due to greenhouse gas emissions and decreasing sea ice (albedo-feedbacks), and this could lead to increased warming through increased evaporation and a concomitant decrease in soil moisture resulting in higher temperatures through decreased latent heat flux and increased sensible heat flux (Gagnon and Gough 2005). So while there is a multi-decadal warming presently occurring, there are also inter-annual variations related to a coupling-effect of the NAO and ENSO that illustrate the complexity of climatic interactions within the region (Cook et al. 2002). D'Arrigo and Jacoby (1999) pointed out that northern trees can record influences of Arctic air masses, frontal shifts and circulation changes, all of which could affect temperature at the study sites

L. laricina in the TUND region are the most sensitive to climatic fluctuations (Figs. 3&11) and therefore have the most potential in terms of climatic reconstructions. In addition, while increasing spring temperatures had a negative effect on growth of trees within the NFOR region, an opposite effect was observed in tree growth within the TUND region. The NFOR chronologies had the strongest response to warming of summer temperatures and in the future they could exceed the TUND *L. laricina* in their potential for climate reconstruction (Fig. 3-11(a)(d)(g)). However this assumes that other climatic factors do not become limiting (e.g., precipitation) (D'Arrigo and Jacoby 1993; Kirschbaum 2000), which is a possibility for the trees of the area as most of the chronologies were negatively correlated with summer PE values (Fig. 5), and warming is predicted to increase during the next century (Gagnon and Gough 2005).

Hemispherical climate

Few significant correlations with the annular modes/hemispheric climatic variability were observed, however the importance of these driving forces cannot be ignored as there are many potential connections with regional climate. When the NAO is in a positive phase during winter, the Icelandic low draws an enhanced southwesterly circulation over the eastern half of North America which prevents Arctic air from plunging southward, resulting in warmer winters (Hurrell et al. 2001). In combination with ENSO, this can result in significantly warmer winters over North America (Rogers 1984). The negative association of TUND *L. laricina* growth during May with the NAO could be an effect of earlier dehardening due to a warmer winter, resulting in higher potential for frost damage when frosts are still prevalent (Hänninen 2006), or cambial activation while the roots are still encased in sub-zero soils. As well, a shift from primarily snowmelt water use to rain water use during the growing season (linked to the positive phase of the NAO) (Welker et al. 2005) could affect TUND *L. laricina* growth, but further research is necessary to properly evaluate this hypothesis.

The AO only affects *L. laricina* trees in the NFOR (negatively) and TUND (positively) regions during July/December of the previous year and July of the current year, respectively (Fig. 7). The NFOR growth response during the winter could be related to a teleconnection between the AO and Churchill winter precipitation (e.g., enhanced snowfall from warmer winter temperatures, resulting in delayed snowmelt), or some other combination of factors, although this connection is not revealed through simple correlations (Table 3-2). The July (t-1) negative growth response of NFOR *L .laricina* and SFOR *P. glauca* with the AO appears to be related to advection (Déry and Wood 2004). Thompson and Wallace (2001) showed that during the negative phase of the AO, northeasterly winds advect relatively warm, moist air from the Labrador Sea to the Hudson Bay lowlands. Conversely, during the positive phase of the AO, northwesterly winds move relatively cool, dry air from the Canadian archipelago to the Hudson Bay area. As such, a connection exists between the AO and precipitation and temperature, that could reveal itself through the correlation with Churchill temperatures ($r=0.25$, $p<0.05$) thereby sharing the same negative July (t-1) relationship. As well, SFOR *P. glauca* is negatively affected by conditions during July (t-1) while *P. mariana* was positively affected by conditions in the summer (t) indicating potential differences in response times of the two species to the AO.

ENSO appeared to have little effect on radial growth with the exception of *P. glauca* within the NFOR region, where growth was significantly positively correlated with the ENSO in summer (Fig. 8). However the effects of ENSO are experienced primarily during the winter months in northern North America (Joseph and Nigam 2006). This is due to changes in advection of heat (e.g., southeasterly flow north of 30^{o}N) causing warmer winters during positive (El Niño) ENSO phases. Thus even eastern Canada, despite northeasterly winds, is warmer due to the advection of maritime air (Joseph and Nigam 2006). The summer relationship could be explained by the significant positive correlation of ENSO with temperatures during March (Table 3-2). As well, warm temperatures over North America during summer, due to ocean-atmosphere dynamics in the north Pacific that are partially linked to the ENSO, likely exerted an influence on summer tree growth (Lau et al. 2004).

The PDO was not significantly correlated with tree growth with the exception of November of the previous year within the TUND region (Fig. 8). This could be because of the PDO link with decreased cyclone frequency in the Arctic (Wang et al. 2006). Moreover, as the PDO is negatively correlated with Churchill precipitation (Table 3-2), an increase in the PDO could result in a lack of precipitation in the form of snow required to insulate the rooting zone during the autumnal thermal overturn, thereby chilling the roots.

Mid-century decrease in correlation between tree growth and climate

The decoupling of radial growth with temperature (and to some extent, the NAO, AO and PDO) during the late-1950s through the early-1980s was evident in all chronologies in the study area. However, this was less obvious in the SFOR chronologies, particularly for the *P. glauca* index which was highly correlated during the mid-1960s. It has been suggested that the attenuation of correlation was due to a shift in atmospheric circulation which drove shifts in temperate air mass distributions during the summer months (Girardin et al. 2005; Scott et al. 1988). As well, Briffa et al. (2002; 1998) alluded to potential factors reducing the sensitivity of tree growth to temperature such as reduced soil moisture from warmer springs and earlier snow melt or unknown anthropogenic influences.

The increase in correlation with summer temperatures after the 1970s has been attributed to a return to arctic conditions (Scott et al. 1988). It is noteworthy that within the last several years summer temperature departures from the 1961-

2000 mean were 2-3°C, which improved the visual agreement between actual and modeled temperatures in the NFOR chronologies during the last 3 years (Fig. 3-11).

Inter-chronology correlations

The correlations among chronologies decrease noticeably as years from present increase, with the exception of those from the NFOR zone. This is likely due to a smaller sample depth and hence, decreased signal-to-noise ratio, earlier in the chronologies and as the NFOR chronologies are well-replicated, the correlations do not decrease as much as at the other sites. Furthermore, as the ages of most trees sampled in the TUND region fall within the 20th century and sample depth decreases abruptly prior to then, correlations among the chronologies would decrease as well due to decreased replication (Cook and Kairiukstis 1990). There is a strong correlation between the NFOR and TUND chronologies, suggesting common environmental influences. The low correlations between the NFOR / TUND, and the SFOR chronologies suggests that the Southern Forest zone of Wapusk NP is influenced by different environmental factors and this conclusion is also confirmed by the low correlations with Churchill climate data. There are several potential reasons why correlations with climate are low for *P. mariana* within the SFOR zone, such as: (i) subtle changes in the seasonality of temperature and precipitation (Groisman et al. 1994) resulting in pronounced disparity in climate (such as a move to warmer springs and earlier snowmelt) (Kirschbaum 2000); (ii) increased insect herbivory and competition with other plants (Fleming and Volney 1995); or (iii) higher UVB levels resulting in decreased growth (Briffa et al. 1998). However, it is curious that the same response was not exhibited by *P. glauca* in the same stands. Further research is needed to determine the primary growth-limiting factor(s) for *P. mariana* in the southern forest of Wapusk NP.

Conclusions

A complex interaction between synoptic/regional climate, topography, tree physiology, and exogenous and endogenous stand effects generates the radial growth pattern within the forest-tundra ecotone in northern Manitoba. Summer temperatures are the primary factor limiting growth within the northern forest and central tundra of Wapusk NP, with a breakdown in correlation with temperature in the southern forest region. Autumn temperatures are also important; particularly for *L. laricina*. Spring temperatures are detrimental in the north and beneficial to growth in the central region, likely due to insulating effects of the snowpack. This illustrates the importance of timing of enhanced snowpack on radial growth (e.g., spring versus autumn) and the disparity in growth response along a latitudinal gradient within the park.

The positive trend in the NAO could affect regional temperature and precipitation patterns around Churchill through teleconnections with ENSO, resulting in warmer winters, which could prove beneficial (longer growing season) or detrimental (premature dehardening) to growth. As well, despite the advection of cool, dry air from northern Canada to the Hudson Bay lowlands due to a recent upward tendency in the AO, positive ENSO phases advect heat from the south resulting in warmer winters. The PDO also appears to negatively affect precipitation at a crucial time (autumnal overturn) when tree roots require insulation from the decreasing air temperatures.

The correlation between radial growth and temperature, as well as all of the climatological oscillations (with the exception of the AO), have become decoupled in recent years for reasons that are not yet apparent, though it is likely related to a decreasing sensitivity of tree growth to temperature due to a superseding signal present in the chronologies. Much of the scientific literature on the subject alludes to moisture stress as the source of that signal (Groisman et al. 1994; Jacoby and D'Arrigo 1995; Barber et al. 2000; D'Arrigo et al. 2004; Wilmking et al. 2005), among many other hypotheses such as increasing atmospheric CO_2, higher levels of pollutant transport, changes in soil chemistry and increased UV-B levels (Briffa et al. 1998). However, it seems that a change in the seasonality of the temperature response of trees (Briffa et al. 2002) could be a dominant factor in the reduced sensitivity of trees in the western Hudson Bay Lowlands as illustrated by the greater correlation with spring temperatures of the northernmost trees (Fig. 3-3). In addition, the declining correlations of tree growth with climatological oscillations during the 20th century (Figs. 3-10 & 3-11) are indicative that the oscillations have less influence on climate variability within the Hudson Bay Lowlands. In addition, the marked variability of the correlations (Figs. 3-10 & 3-11) suggests the magnitude of the oscillations influence on tree growth has been reduced in recent times (Gedalof and Mantua 2002).

The northern forest and central tundra chronologies were significantly correlated, and the correlation of the chronologies to that from the southern forest has become significantly negative in recent years when prior to this it was uncorrelated. This circumstance could be related to different environmental conditions within the northern and southern forest that are not available via instrumental the instrumental record (e.g., soil moisture, active layer depth).

Future work should include additional sampling, particularly of *L. laricina* within the central and southern regions of Wapusk NP as well as *P. mariana* from the southern region. This would bring the chronologies up to date and resolve signal-to-noise issues related to low sample size within the tundra *L. laricina* chronology and the earlier portion of the rest of the chronologies. This would enable evaluation of the tundra *L. laricina* chronology for regional paleoclimatic reconstructions. As well, a more detailed investigation into teleconnections and feedbacks between climatological oscillations and regional climate should be undertaken in order to resolve the effects of the oscillations on radial growth.

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CHAPTER 4

Synthesis and conclusion

Introduction

This thesis has dealt with tree growth and recruitment dynamics in northern Manitoba. The main purposes and objectives were:

1. Determine the potential for treeline migration within upland and wetland environments near Churchill, Manitoba (Chapter two)
    - i. determine treeline response to recent and former environmental change through age structure- and tree growth-climate analyses and,
    - ii. examine differences in stand infilling and forest expansion within upland and wetland environments
2. Assess the various climatological factors affecting radial growth across environmental gradients within Wapusk NP – Northern Hudson Bay Lowland (Chapter three)
    - i. characterize spatial and temporal variations in tree-ring radial growth in Wapusk NP and the adjacent Churchill Wildlife Management Area (CWMA) and,
    - ii. evaluate the viability of the tree-ring record for paleoclimatic reconstruction for the Northern Hudson Bay Lowland.

Summary of results

Tree recruitment and vigor: upland versus wetland localities

It was found that wetland trees were more sensitive to temperature fluctuations while upland forests were more susceptible to drought. Tree vigor improved in the last several decades and tree height increased during the past century, likely reflecting a change from stunted growth forms to arborescent individuals. This transition can also increase reproductive capabilities of trees, a characteristic which could be the last obstacle in successful colonization of the tundra by forest (Sirois and Payette 1991; Asselin and Payette 2005). In addition, historical rates of recruitment did not differ considerably between upland and wetland sites ($r=0.61$, $p<0.05$) indicating that ground cover (e.g., lichens at uplands versus mosses at wetlands) had no significant influence on establishment up to 1900. This is based on the assumption that the ground cover does not change appreciably throughout time, and would not influence the results here. This assumption seems valid since recruitment essentially mirrored radial growth, and both can be adequately explained by climate. The warming in recent years set the conditions for the further infilling of upland and wetland forest stands and likely increased recruitment within the forest-tundra localities around Churchill. However, characterization of establishment rates following 1900 will be necessary to make informed predictions on the future status of the treeline.

Radial growth response to climate: forest versus tundra

A complex interaction between factors such as synoptic/regional climate, topography, tree physiology, and exogenous/endogenous stand characteristics ultimately results in the radial growth pattern of trees within the forest-tundra ecotone. Summer temperature was the primary factor limiting growth within the northern forest and central tundra of Wapusk NP, but this was not the case in the southern forest region. Autumn temperatures were also important; particularly for *Larix laricina* (Du Roi) K. Koch. Spring temperatures were detrimental in the north and beneficial to growth in the central region, likely due to insulating effects of the snowpack. This illustrates the importance of timing of enhanced snowpack on radial growth (e.g., spring versus autumn) and the disparity in growth response along a latitudinal gradient within the park.

The positive relationship with the North Atlantic Oscillation (NAO) could reflect a link with regional temperature and precipitation patterns around Churchill through teleconnections with the El Niño Southern Oscillation (ENSO). The resulting warmer winters, could prove beneficial if longer growing seasons resulted or detrimental if premature dehardening or dormancy break lead to tissue damage. Additionally, positive ENSO phases advect heat from the south resulting in warmer winters despite the advection of cool, dry northern air to the Hudson Bay lowlands via a recent upward tendency in the Arctic Oscillation (AO). The Pacific Decadal Oscillation (PDO) also appears to negatively affect precipitation at a crucial time (autumnal overturn) when tree roots require insulation as the air temperatures drop.

The correlation between radial growth and temperature, as well as all of the climatological oscillations (with the exception of the AO), have decreased in recent years for reasons that are not yet apparent, though it is likely related to a decreasing sensitivity of tree growth to temperature due to a superseding signal present in the chronologies. Much of the scientific literature on the subject alludes to moisture stress as the source of that signal (Groisman et al. 1994; Jacoby and D'Arrigo 1995; Barber et al. 2000; D'Arrigo et al. 2004; Wilmking et al. 2005), among many other hypotheses such as increasing atmospheric CO_2, higher levels of pollutant transport, changes in soil chemistry and increased UV-B levels (Briffa et al. 1998). However, it seems that a change in the seasonality of the temperature response of trees (Briffa et al. 2002) could be a dominant factor in the reduced sensitivity of trees in the western Hudson Bay Lowlands as illustrated by the greater correlation with spring temperatures of the northernmost trees (Fig. 3-3). In addition, the declining correlations of tree growth with climatological oscillations during the 20th century (Figs. 3-10 & 3-11) are indicative that the oscillations have become less dominant modes of climate variability within the Hudson Bay Lowlands. In addition, the marked variability of the correlations (Figs. 3-10 & 3-11) suggests the oscillations may not be coherent over time, as may be their effects on tree growth (Gedalof and Mantua 2002).

The northern forest and central tundra chronologies were significantly correlated, and the association of these chronologies to that of the southern forest has recently changed from unrelated to negatively correlated. This could be related to site-specific environmental factors that have not appeared in the Churchill and Gillam climate records (e.g., warmer springs and earlier snowmelt), but further investigation is necessary to determine the source of this disparity.

It was not unexpected that trees at the northern end of the study area were most sensitive to temperature fluctuations and thus most useful in climatic reconstructions, particularly TUND *L. laricina* and NFOR *P. mariana* (Fig. 3-11). However, there is an important caveat to using recent periods for calibration, as articulated by Briffa et al. (1998; 2000), as regression coefficients based on recent temperatures will cause past temperatures to be overestimated and the extent of 20th century warming to be underestimated.

What does this mean for the forest-tundra of northern Manitoba?

There were several key findings arising from these investigations which have implications for forest-tundra dynamics in northern Manitoba. While there is a certain elegance in forecasting binary scenarios (e.g., this will happen or it will not), it will undoubtedly involve some level of simplification that cannot be avoided. The predictions are based on the findings presented above and are intended to apply at the local and landscape scales.

Surface air temperatures are predicted to increase over the next century (IPCC 2007). It has been shown that temperatures play a significant role in regulating tree growth (Figs. 2-5 and 3-9) and that while there is a decreased sensitivity to July/summer temperatures in recent decades, spring and September temperatures are becoming increasingly more crucial in radial growth of trees in northern Manitoba. Therefore, if temperatures do continue to increase, radial growth of all three species investigated here will increase throughout Wapusk NP and the Northern Hudson Bay Lowland. There are however some differences to be aware of:

1. Northern forest versus tundra trees – as illustrated in Chapter three, there appears to be a distinct difference in the response of northern forest and tundra trees to spring temperatures which appears to be related to snowpack. However, precipitation over northern Canada is decreasing with more frequent positive (negative) phases of the AO and the PDO (ENSO) (Déry and Wood 2005) which could result in reduced accumulation of snow within forest environments. Thus as growth of northern forest trees has previously been quite limited by a thick snow pack and short growing season, an increase in spring temperatures and reduction in snowpack persistence will likely result in increased tree vigor with further warming. Both northern forest and tundra trees are set to increase in radial growth production in the near future, as well as increase in sexual reproduction resulting in increased seedling production and improved establishment. However, further inland within the central tundra, recruitment could be limited due to paludification as the extent of thermokarst increases.
2. Upland versus wetland growth – As stated above, the greatest changes in forest-tundra structure will be within the northern forest and central tundra localities. Focusing on the northern forested area, there will likely be distinct differences between upland and wetland sites in terms of tree growth and recruitment. As upland localities are more susceptible to drought, particularly in July (Fig. 2-4), increased

growing season temperatures could eventually lead to drought stress as precipitation decreases due to the mechanism mentioned earlier.

3. Species-specific differences – All species within the northern portion of the study area expressed increased growth with warming since the Little Ice Age. This has been particularly evident in the last two decades (Fig. 3-2). As well, there has been a marked increase in height of individuals since 1900. Thus, each species seems to be responding favorably to warming, with similar recruitment patterns among the three (Fig. 2-6). Rising temperatures are predicted to drive increases in seedling establishment and vigor. However, other consequences of warming such as paludification make confident predictions difficult.

Recommendations for future work

Future work should include additional sampling, particularly of *L. laricina* within the central and southern regions of Wapusk NP as well as *P. mariana* from the southern region. This would bring the chronologies up to date and resolve signal-to-noise issues related to a paucity of samples within the tundra *L. laricina* chronology. This would improve resolution and reliability of the tundra *L. laricina* chronology for regional paleoclimatic reconstructions. As well, a more detailed investigation into teleconnections and feedbacks between climatological oscillations and regional climate should be undertaken in order to resolve the effects of the oscillations on radial growth.

Improvements to the sampling methods to bring them in line with several other researchers (Szeicz and MacDonald 1995; Lloyd and Fastie 2003) would be desirable. This basic approach involves ageing trees sampling within plots located at different latitudes spanning the forest-tundra ecotone. The age structures developed for each plot would be analyzed to assess whether there has been any change in densities with time. These data could then be compared to values from corresponding higher or lower latitudes to determine whether there has been a change in the location of the treeline (Kearney 1982; Danby 2007). Standardized ring-width chronologies could be compiled for each plot and species sampled and comparisons of vigor could also be made. Sampling should also include saplings and seedlings in order to accurately represent younger age classes, in light of recent warming. Thus the status of mature and juvenile trees could be established and past and present rates of growth and recruitment could be evaluated within a site and over the region. Such projects are already in development as part of the International Polar Year (IPY) (http://www.ipy.org) and should yield valuable insights into forest-tundra dynamics and effects on related ecosystems.

Conclusions

The research presented here is the first multi-species study of the forest-tundra ecotone within the northern Hudson Bay Lowland of Manitoba. There have been other tree-ring studies completed in the vicinity of Churchill, but none has been completed within Wapusk and the objectives of those studies have differed from this one. It was the aim of this research to evaluate pattern and process within the forest-tundra of northern Manitoba and determine the status of the treeline. To some extent this was achieved, but limitations inherent within the sample selection and density have restricted the inferences that can be made. This investigation has shown that, historically, treeline trees have responded favorably to warm temperatures by way of increased vigor and seedling establishment and are presently responding favorably to the temperature increases of the last two decades. Given the evidence (e.g., tree-growth form individuals, increased vigor and recruitment of treeline trees) it appears that a poleward shift of treeline is imminent or underway.

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APPENDICES

Upland and wetland RCS ring-width chronologies

WSU RCS
Annual values

Date	0	1	2	3	4	5	6	7	8	9
1650	0.04	0.11	0.11	0.21	0.21	0.28	0.19	0.21	0.17	0.14
1660	0.12	0.24	0.29	0.39	0.42	0.69	0.83	0.63	0.96	0.75
1670	0.62	0.78	0.72	0.43	0.58	0.73	0.62	0.54	0.46	0.59
1680	0.61	0.90	1.19	0.80	1.26	0.94	0.85	0.93	0.90	1.20
1690	1.23	1.01	1.08	1.38	0.94	1.05	0.83	0.80	0.98	0.90
1700	0.92	0.84	1.16	1.15	0.87	1.10	0.83	1.00	1.15	0.86
1710	1.24	0.97	1.01	1.12	0.87	0.85	0.71	0.95	0.92	1.08
1720	0.87	1.05	1.05	1.11	1.21	1.13	1.12	1.05	1.05	1.00
1730	0.98	0.92	0.92	0.92	0.85	0.96	1.08	1.01	1.20	1.13
1740	1.01	0.71	0.77	0.68	0.91	0.85	0.79	1.05	0.96	1.01
1750	0.80	0.90	0.99	0.99	1.09	1.10	0.97	0.81	0.85	0.64
1760	0.88	0.94	1.09	1.01	0.93	1.01	1.13	1.21	1.13	1.10
1770	1.08	0.82	0.99	0.76	0.90	0.99	1.18	1.12	0.93	0.81
1780	0.94	0.95	1.07	0.78	1.07	1.08	1.05	0.89	1.09	1.05
1790	1.08	1.07	0.91	0.87	0.98	0.85	1.00	0.81	0.98	0.92
1800	0.75	1.04	0.92	1.04	0.98	1.15	1.01	0.98	0.98	0.90
1810	1.20	1.06	0.99	1.00	1.09	0.99	0.95	0.95	1.01	1.09
1820	1.10	0.87	1.10	0.98	0.94	0.83	1.03	0.79	0.93	0.90
1830	0.93	0.89	0.82	0.91	0.94	0.67	0.74	0.44	0.81	0.65
1840	0.73	0.76	0.66	0.72	0.75	0.74	0.81	0.77	0.75	0.77
1850	0.92	0.76	0.85	0.78	0.80	0.80	0.82	0.84	0.80	0.83
1860	0.68	0.86	0.85	0.89	1.03	0.98	0.95	0.82	0.89	0.74
1870	1.26	0.99	0.91	1.06	0.84	0.91	0.65	0.89	0.94	0.74
1880	0.84	0.76	0.74	0.84	0.95	1.06	1.16	1.32	1.04	0.91
1890	1.06	0.96	0.97	1.01	0.95	1.02	0.90	0.90	1.09	1.11
1900	1.31	1.10	1.29	1.23	1.18	1.25	1.16	1.27	1.13	1.24
1910	1.33	1.20	1.06	1.17	1.05	1.06	1.18	1.22	1.09	1.15
1920	1.19	1.35	1.06	1.10	0.94	1.10	1.26	1.07	1.18	1.20
1930	1.16	1.17	1.38	1.32	1.22	1.14	1.18	1.00	1.06	1.13
1940	1.07	1.19	1.12	1.19	1.23	1.05	1.30	1.29	1.24	0.99
1950	0.88	0.93	0.69	0.85	0.93	0.90	0.86	1.09	0.95	0.98
1960	0.86	1.01	1.03	1.19	1.03	1.14	1.19	1.02	0.93	0.94
1970	0.86	0.69	0.83	0.73	0.93	0.71	0.90	1.01	0.95	0.90
1980	0.75	0.99	0.79	0.97	0.87	0.83	0.87	0.94	0.95	0.89
1990	0.90	0.89	0.65	0.84	0.84	0.89	0.97	0.88	0.82	0.98
2000	1.06	1.22	1.42	1.45						

BSW RCS

Annual values

Date	0	1	2	3	4	5	6	7	8	9
1716	0.39	0.37	0.35	0.46						
1720	0.57	0.54	0.41	0.47	0.35	0.38	0.34	0.37	0.42	0.40
1730	0.44	0.36	0.42	0.46	0.34	0.37	0.47	0.41	0.41	0.31
1740	0.38	0.22	0.22	0.33	0.39	0.31	0.31	0.33	0.36	0.37
1750	0.44	0.46	0.33	0.33	0.45	0.38	0.41	0.20	0.22	0.29
1760	0.23	0.17	0.29	0.35	0.31	0.32	0.41	0.38	0.41	0.47
1770	0.43	0.34	0.34	0.40	0.48	0.45	0.55	0.47	0.38	0.29
1780	0.32	0.40	0.45	0.27	0.36	0.33	0.34	0.35	0.38	0.31
1790	0.33	0.69	0.30	0.32	0.36	0.42	0.41	0.38	0.43	0.53
1800	0.50	0.41	0.54	0.53	0.45	0.57	0.45	0.53	0.41	0.44
1810	0.38	0.44	0.40	0.45	0.42	0.54	0.45	0.37	0.32	0.31
1820	0.42	0.58	0.55	0.58	0.58	0.44	0.66	0.75	0.69	0.75
1830	0.85	0.79	0.77	0.70	0.83	0.80	0.64	0.36	0.47	0.49
1840	0.73	0.63	0.57	0.58	0.65	0.66	0.79	0.92	0.73	0.74
1850	0.99	0.82	0.74	0.69	0.89	0.92	0.68	0.72	0.71	0.83
1860	0.61	0.66	0.75	0.67	0.93	0.93	0.97	0.81	1.07	0.75
1870	1.09	0.98	0.92	0.88	0.80	1.02	0.70	0.84	1.02	0.80
1880	0.96	0.84	0.81	0.88	0.96	0.84	0.90	1.03	0.70	0.60
1890	0.70	0.74	0.74	0.78	0.76	0.86	0.83	0.70	0.82	0.96
1900	1.07	1.14	1.10	1.19	1.08	0.96	1.01	0.99	0.90	1.10
1910	1.43	1.27	1.06	1.10	0.97	0.96	0.94	1.17	0.88	0.99
1920	0.99	1.24	1.01	1.19	0.93	1.09	1.27	1.35	1.51	1.19
1930	1.38	1.35	1.43	1.35	1.32	1.17	1.28	1.04	1.31	1.29
1940	1.26	1.45	1.23	1.32	1.33	1.06	1.06	1.49	1.44	1.12
1950	0.97	1.11	0.90	0.99	1.17	1.19	1.23	1.22	1.18	1.19
1960	1.04	1.29	1.16	1.25	1.16	0.99	1.19	1.25	1.15	1.14
1970	1.01	0.84	1.01	0.69	0.92	0.67	0.99	0.99	1.10	1.04
1980	0.74	1.02	0.95	1.16	1.04	0.88	0.89	0.98	0.96	1.04
1990	1.06	1.05	0.69	0.75	0.88	0.97	1.13	0.96	1.10	1.18
2000	0.96	1.13	1.12							

Northern forest, Central tundra and Southern forest standardized ring-width chronologies

NFOR Pg Res

Annual values

Date	0	1	2	3	4	5	6	7	8	9
1745	0.72	1.08	1.26	1.03	1.18					
1750	0.83	1.05	1.03	0.85	1.15	1.20	1.11	0.82	0.93	0.81
1760	1.16	1.05	1.36	0.81	0.91	0.89	0.94	1.07	0.77	1.14
1770	1.08	0.79	0.87	1.08	1.11	1.04	1.03	1.09	0.75	0.74
1780	1.11	0.96	1.15	0.72	1.04	1.05	1.03	0.85	1.22	1.31
1790	0.95	1.27	0.97	0.99	1.05	1.01	1.33	1.06	1.24	1.14
1800	0.81	1.20	1.29	1.11	0.88	1.11	0.76	1.08	0.96	0.80
1810	1.28	0.91	0.95	1.02	1.13	1.06	0.85	1.09	1.01	1.04
1820	1.27	0.80	1.27	1.02	0.95	0.70	1.01	0.84	1.09	1.06
1830	1.04	0.95	1.12	0.88	1.05	0.64	0.94	0.69	1.07	1.08
1840	0.83	1.04	0.72	0.98	1.12	1.01	0.90	1.04	0.93	0.94
1850	1.10	0.81	0.90	1.00	0.91	0.98	0.92	0.90	1.00	0.98
1860	0.88	1.28	0.88	0.92	1.19	0.97	1.01	0.92	0.95	0.82
1870	1.26	0.90	0.81	1.02	0.80	0.99	0.83	0.95	0.84	0.83
1880	1.03	0.97	0.97	0.91	1.29	1.21	1.25	1.51	0.84	0.78
1890	1.07	1.04	1.00	1.10	0.93	1.16	0.85	0.94	1.04	0.96
1900	1.17	0.92	1.07	1.06	0.97	1.03	0.90	1.10	0.91	1.06
1910	1.09	0.93	0.89	1.00	0.86	0.96	1.10	1.06	0.90	0.98
1920	1.02	1.07	0.81	0.97	0.89	1.08	1.16	0.87	1.05	1.05
1930	0.98	0.99	1.21	1.04	0.97	0.99	1.02	0.88	1.02	1.05
1940	1.00	1.09	1.07	1.08	1.11	0.91	1.27	1.07	1.03	0.84
1950	0.90	0.97	0.78	1.01	1.06	0.94	0.94	1.19	0.91	0.97
1960	0.90	1.07	1.10	1.18	0.93	1.18	1.09	0.92	0.92	0.92
1970	0.92	0.79	1.00	0.90	1.05	0.83	1.07	1.16	0.97	0.96
1980	0.84	1.16	0.87	1.12	0.92	0.94	1.00	1.06	1.01	0.90
1990	1.01	0.94	0.74	1.07	0.95	0.97	0.98	0.98	0.93	1.13
2000	1.14	1.22	1.19	1.05						

NFOR Pm Res

Annual values

Date	0	1	2	3	4	5	6	7	8	9
1719	1.28									
1720	1.45	1.00	0.73	1.06	0.78	0.96	0.90	0.98	1.11	1.01
1730	1.07	0.86	1.07	1.13	0.78	0.97	1.24	0.98	1.00	0.76
1740	1.07	0.63	0.79	1.15	1.22	0.86	0.90	1.02	1.09	1.07
1750	1.24	1.22	0.93	0.86	0.99	1.10	0.86	0.65	0.79	0.73
1760	0.83	0.91	1.49	0.99	0.89	1.08	1.06	1.01	1.05	1.19
1770	0.90	0.88	1.03	1.03	1.19	1.04	1.17	1.08	1.04	0.76
1780	1.30	1.19	1.00	0.59	1.04	1.01	0.87	0.95	0.91	1.04
1790	1.03	0.83	0.75	0.96	1.07	1.11	0.99	0.84	0.91	0.92
1800	0.86	1.07	1.04	1.07	1.02	1.15	0.95	1.21	0.87	0.95
1810	1.11	1.03	0.92	1.02	1.00	1.03	0.89	0.93	0.88	0.93
1820	0.96	1.04	1.00	0.93	0.84	0.91	1.13	0.99	1.10	1.19
1830	1.09	0.99	1.02	0.87	1.06	0.84	0.98	0.70	1.05	0.97
1840	1.14	1.05	0.88	1.02	0.91	0.95	1.07	1.08	0.90	0.91
1850	1.04	0.98	0.94	0.91	0.99	1.05	0.93	1.02	1.05	0.99
1860	0.97	1.13	1.09	0.98	1.07	1.10	1.05	0.94	0.97	0.93
1870	1.19	0.94	0.95	1.06	0.98	1.08	0.84	1.01	1.24	0.94
1880	1.03	0.95	0.97	1.03	1.07	0.96	0.98	1.03	0.86	0.84
1890	0.94	0.96	0.94	0.97	0.92	1.05	0.86	0.88	0.97	1.02
1900	1.07	0.96	1.01	1.02	0.91	0.97	1.01	0.92	0.94	1.08
1910	1.08	1.03	1.08	1.07	0.86	0.92	1.01	1.11	0.91	0.91
1920	1.02	1.05	0.80	1.02	0.95	1.03	1.02	1.15	1.23	0.94
1930	0.99	0.91	1.10	0.97	1.04	1.06	1.02	0.80	1.18	1.01
1940	1.05	1.03	1.05	1.12	0.99	0.89	1.02	0.96	1.05	0.87
1950	0.90	1.01	0.81	1.02	1.11	1.08	1.02	1.04	0.94	0.93
1960	0.97	1.11	1.04	1.02	0.97	1.00	1.07	0.92	0.97	1.06
1970	0.95	0.71	1.09	0.85	1.00	0.87	1.10	0.97	1.04	1.01
1980	0.77	1.14	0.90	1.18	1.02	0.84	0.96	1.05	0.99	0.97
1990	0.94	1.01	0.71	0.93	0.98	0.98	1.00	0.99	0.93	1.16
2000	1.06	1.03	1.16	1.01						

NFOR Ll Res
Annual values

Date	0	1	2	3	4	5	6	7	8	9
1752	1.01	1.47	0.95	1.53	0.45	0.96	1.29	0.63		
1760	0.69	0.73	0.95	1.05	0.94	1.46	0.63	1.11	1.28	1.02
1770	1.29	0.65	1.14	1.18	1.47	0.56	1.13	0.92	0.82	0.62
1780	1.26	0.80	0.60	0.55	0.95	1.15	0.72	0.76	1.00	1.05
1790	0.76	1.07	0.54	0.86	0.82	1.01	0.90	1.03	1.14	1.54
1800	0.75	0.77	1.09	1.08	1.05	1.42	0.83	1.15	0.90	1.00
1810	1.09	1.11	0.85	0.84	1.09	1.22	0.85	0.75	0.84	1.01
1820	1.24	1.03	0.90	1.03	1.05	0.73	1.13	1.21	0.87	0.96
1830	1.18	1.07	1.06	1.02	1.28	0.99	0.73	0.59	1.01	0.99
1840	0.99	0.81	0.73	0.83	1.10	1.03	1.28	1.33	0.91	1.00
1850	1.24	0.86	0.98	0.89	1.28	1.17	0.83	0.76	0.79	1.00
1860	0.66	0.89	1.01	0.84	1.15	1.06	1.09	0.81	1.28	0.74
1870	1.23	1.03	0.89	0.96	0.93	1.20	0.72	1.02	1.19	0.73
1880	1.12	0.88	0.90	1.06	1.14	0.91	1.08	1.26	0.64	0.65
1890	0.97	0.97	0.91	0.97	0.90	1.05	0.97	0.81	0.93	1.10
1900	1.20	1.03	0.98	1.12	1.04	0.81	0.92	0.98	0.87	1.04
1910	1.45	1.03	0.82	1.01	0.96	0.86	0.88	1.19	0.76	1.04
1920	1.00	1.19	0.86	1.09	0.68	0.96	1.01	1.04	1.11	0.81
1930	1.19	1.18	1.15	1.09	1.02	0.85	1.10	0.84	1.05	1.15
1940	0.89	1.19	0.78	1.06	1.11	0.80	0.86	1.50	1.11	0.83
1950	0.74	1.09	0.79	0.91	1.08	1.05	1.03	1.12	1.06	1.12
1960	0.87	1.19	0.98	1.19	0.93	0.78	1.03	1.15	1.01	1.05
1970	0.87	0.84	1.01	0.64	1.04	0.70	1.12	1.03	1.08	1.02
1980	0.74	1.08	0.95	1.10	0.94	0.80	0.89	1.04	0.98	1.10
1990	1.03	1.02	0.60	0.86	1.13	1.15	1.37	0.77	1.16	1.06
2000	0.87	1.11	1.66							

TUND Pg Res

Annual values

Date	0	1	2	3	4	5	6	7	8	9
1775	1.13	0.85	1.43	1.02	0.71					
1780	0.78	1.29	0.98	1.21	0.76	1.15	0.90	1.14	1.34	0.97
1790	1.53	1.74	0.77	0.68	0.91	1.28	1.35	1.24	0.81	1.02
1800	0.76	0.65	0.96	0.85	0.90	0.86	1.03	0.95	1.07	0.81
1810	0.89	1.17	1.25	0.88	1.01	1.35	0.90	0.91	0.94	0.99
1820	1.16	1.08	0.84	1.23	1.18	0.83	0.78	0.95	0.61	0.85
1830	0.91	1.25	0.94	0.86	0.80	0.57	0.64	0.71	0.77	0.79
1840	1.47	1.06	0.77	0.88	0.85	1.01	1.04	0.86	0.87	1.04
1850	0.76	0.58	0.99	1.02	1.07	1.06	1.09	1.15	0.99	0.95
1860	0.88	1.05	0.98	1.05	1.29	0.80	1.13	0.93	1.15	0.77
1870	1.46	1.13	0.91	0.94	0.83	1.04	0.83	1.14	1.01	1.01
1880	1.23	1.12	0.87	1.00	1.14	1.04	1.05	0.88	0.97	0.86
1890	1.06	0.95	0.99	0.96	0.93	0.87	0.99	1.06	0.88	1.03
1900	1.17	0.79	1.20	1.08	0.75	0.98	0.98	1.02	1.08	1.11
1910	1.05	1.04	1.13	1.04	0.79	0.92	0.95	1.04	0.85	0.89
1920	0.91	1.14	0.85	1.00	0.95	0.98	1.02	0.92	1.11	0.95
1930	1.09	0.91	1.24	0.96	0.96	1.15	0.90	0.86	1.21	0.91
1940	1.04	1.07	0.95	1.08	1.04	0.75	1.11	0.92	1.11	0.81
1950	0.94	0.97	0.88	1.00	1.08	1.00	1.04	1.09	0.95	1.00
1960	0.99	0.98	1.03	1.10	0.89	1.02	1.21	0.78	0.93	1.01
1970	1.05	0.86	1.09	0.96	1.01	0.89	1.12	1.01	0.97	1.12
1980	0.84	1.30	0.88	1.23	0.89	0.93	1.05	1.05	0.94	0.93
1990	0.97	1.06	0.61	1.13	1.02	0.91	0.93	1.00	0.83	1.05
2000	1.04	1.14	0.99	1.02	0.90					

TUND Pm Res

Annual values

Date	0	1	2	3	4	5	6	7	8	9
1740	0.81	1.09	1.77	1.31	1.47	1.09	0.30	0.44	1.17	0.79
1750	0.81	0.73	0.99	0.79	1.01	1.04	1.35	0.99	0.84	1.17
1760	1.36	1.36	0.32	0.88	1.08	0.65	1.05	1.21	1.34	0.89
1770	0.74	0.92	0.83	0.84	1.08	1.09	0.73	0.99	1.05	1.15
1780	1.21	1.07	1.58	1.02	0.79	0.92	1.25	0.92	1.11	0.57
1790	1.00	1.19	0.84	0.78	1.02	1.27	1.20	0.88	0.94	1.56
1800	1.15	1.61	1.25	0.92	0.72	1.11	1.03	1.26	1.04	0.74
1810	0.83	1.03	0.95	1.09	0.94	0.91	0.98	0.89	0.69	0.76
1820	1.01	1.09	0.78	1.12	1.14	0.93	0.86	1.16	1.26	1.03
1830	1.28	0.85	0.92	0.89	0.85	1.15	0.90	0.86	0.87	0.71
1840	1.13	1.10	0.74	0.97	0.84	0.98	0.84	0.92	0.88	0.85
1850	0.87	0.94	0.97	0.87	1.03	1.03	0.90	0.97	0.98	1.02
1860	1.01	1.04	1.01	0.90	0.97	0.94	1.07	1.03	0.98	0.84
1870	1.07	1.05	0.99	1.01	0.96	1.05	1.00	1.04	1.14	0.95
1880	1.01	1.01	1.07	1.04	0.98	0.92	0.96	0.94	0.91	0.88
1890	1.03	0.94	1.06	1.08	0.96	1.02	0.92	0.94	1.00	1.00
1900	1.02	0.85	1.06	1.04	0.98	1.03	1.03	1.01	1.05	1.02
1910	1.05	0.99	0.97	1.02	0.85	0.85	0.94	1.05	0.90	0.91
1920	0.96	1.09	0.84	0.90	0.96	1.00	0.97	0.96	1.06	0.96
1930	0.95	0.99	1.06	0.97	1.05	1.16	0.92	0.97	1.01	0.96
1940	1.08	1.02	1.05	1.07	0.99	0.78	1.10	0.93	1.12	0.79
1950	0.93	0.98	0.82	0.96	1.10	1.14	1.05	1.08	0.94	1.09
1960	1.03	1.02	0.90	1.06	1.06	0.99	1.14	0.76	0.88	1.19
1970	1.02	0.85	1.06	0.89	0.98	0.96	1.01	1.00	1.05	1.02
1980	0.94	1.18	0.93	1.11	0.91	0.81	0.98	1.06	0.98	0.84
1990	0.96	1.09	0.70	1.04	1.05	0.93	0.90	0.93	0.87	1.05
2000	1.02	1.07	1.03	1.03	0.96					

TUND Ll Res

Annual values

Date	0	1	2	3	4	5	6	7	8	9
1928	0.39	0.80								
1930	0.91	1.51	1.00	0.78	0.61	0.80	0.76	1.04	1.22	1.59
1940	1.11	2.21	0.57	1.20	1.51	0.69	0.70	1.13	0.97	1.04
1950	0.83	0.84	0.87	1.16	1.36	1.11	0.96	1.28	0.73	1.31
1960	0.94	1.09	0.96	1.21	0.74	0.76	1.32	0.82	0.80	1.15
1970	1.27	1.02	1.06	0.49	1.36	0.81	1.24	0.80	0.91	0.94
1980	0.84	1.12	0.84	1.34	1.11	0.61	0.86	0.86	1.06	1.03
1990	0.76	1.10	0.57	1.02	1.05	1.13	1.23	0.84	0.97	1.29
2000	1.01	1.12	1.17	1.26						

SFOR Pg Res
Annual values

Date	0	1	2	3	4	5	6	7	8	9
1731	1.26	1.07	1.27	0.80	0.81	1.14	1.51	1.05	1.02	
1740	0.84	0.82	0.99	1.11	0.90	1.14	0.93	0.87	1.02	1.03
1750	0.90	1.03	0.86	1.00	1.06	0.98	1.11	1.02	0.86	0.96
1760	0.81	0.95	1.00	0.95	0.83	0.94	1.06	0.80	0.89	1.12
1770	0.89	0.87	1.13	1.21	1.06	1.14	1.20	1.04	0.82	0.68
1780	0.94	0.89	1.01	0.97	1.15	0.88	0.82	0.90	0.85	1.09
1790	0.97	0.86	0.97	1.11	0.93	1.13	1.22	0.86	0.92	0.99
1800	0.96	1.14	1.06	0.89	0.91	1.19	1.14	1.41	0.90	0.90
1810	1.08	0.78	0.76	0.91	0.84	0.74	0.99	0.85	0.98	0.85
1820	1.21	1.18	1.07	1.13	1.04	0.80	1.13	1.15	1.17	1.10
1830	1.00	1.13	0.93	1.10	0.93	0.87	0.86	0.64	0.99	0.86
1840	1.05	1.02	0.97	1.10	1.02	0.94	1.01	0.91	0.84	1.02
1850	1.04	0.83	1.08	0.80	0.91	0.96	1.12	0.95	1.10	1.02
1860	0.94	1.26	1.01	1.05	1.20	0.79	1.13	0.92	1.08	0.75
1870	1.16	1.05	0.87	1.08	0.87	0.99	0.85	1.03	1.08	0.95
1880	1.07	0.95	1.07	1.11	0.93	1.08	0.89	0.95	0.74	0.85
1890	1.02	1.01	0.91	0.97	1.01	0.96	0.95	0.90	1.07	1.06
1900	1.07	0.90	1.00	1.06	0.87	1.06	1.02	0.98	1.02	1.02
1910	1.05	0.98	0.99	1.06	0.87	0.89	0.93	1.09	0.96	0.96
1920	0.92	1.07	0.88	1.12	1.03	1.02	1.03	0.95	1.10	0.94
1930	1.06	0.76	0.97	0.91	1.16	1.22	0.87	1.01	1.18	0.99
1940	1.10	0.95	1.03	1.04	0.99	0.83	1.09	0.88	1.12	0.92
1950	1.05	1.08	0.77	1.05	1.16	1.05	1.03	1.10	0.99	1.07
1960	0.84	1.11	1.02	1.10	0.93	1.12	1.24	0.80	0.76	1.08
1970	1.02	0.75	1.11	0.85	0.95	0.76	1.10	0.91	1.00	0.99
1980	0.78	1.26	0.78	1.18	0.89	0.90	1.15	1.07	0.82	0.96
1990	0.99	1.16	0.56	1.10	1.15	0.84	0.97	0.90	0.87	1.08
2000	1.04	1.22	1.13	1.15	0.82					

SFOR Pm Res
Annual values

Date	0	1	2	3	4	5	6	7	8	9
1745	0.59	0.76	0.83	1.05	1.15					
1750	0.95	1.22	1.20	1.28	1.04	1.22	1.24	0.76	1.01	0.82
1760	1.07	1.05	1.16	0.87	0.72	0.84	0.73	0.76	1.06	1.28
1770	0.82	1.41	1.03	1.11	0.93	0.82	1.24	1.04	0.93	1.17
1780	0.88	1.11	1.16	0.58	1.02	1.12	0.91	1.02	1.17	0.87
1790	0.99	1.04	0.95	1.01	0.95	1.17	1.13	0.97	0.99	1.15
1800	1.01	1.20	1.15	1.02	1.13	1.17	1.00	1.00	0.97	0.82
1810	0.96	1.07	1.08	0.90	0.98	1.05	0.73	0.95	1.05	0.78
1820	1.06	1.09	1.14	1.01	1.01	0.88	0.92	0.97	0.95	0.88
1830	0.98	1.07	0.94	0.83	1.17	1.00	0.93	0.71	0.96	0.91
1840	1.03	1.04	0.97	0.96	0.92	1.05	0.97	1.07	0.94	0.98
1850	1.09	1.02	1.00	1.01	1.02	1.05	0.97	1.00	1.12	0.98
1860	0.93	1.18	0.92	1.00	1.13	1.04	1.17	0.82	0.86	0.83
1870	1.18	0.95	0.87	1.02	0.96	1.06	0.90	0.98	1.07	0.92
1880	1.05	1.11	1.00	1.24	1.01	1.02	0.97	0.98	0.86	0.83
1890	0.90	0.92	0.96	0.98	1.03	0.98	0.95	0.85	0.97	0.90
1900	0.98	0.92	0.91	1.06	0.88	0.97	0.97	1.01	1.08	1.01
1910	1.07	1.06	0.95	1.02	0.93	0.94	0.92	1.13	0.94	1.03
1920	0.86	1.01	0.89	0.97	1.02	0.91	0.99	0.91	0.99	1.00
1930	0.98	0.98	1.04	0.94	1.12	1.23	0.86	0.95	1.00	1.05
1940	1.07	1.09	1.08	0.97	0.99	0.96	1.05	0.85	0.98	0.91
1950	0.96	1.05	0.83	1.05	1.07	1.07	0.98	1.09	1.06	1.19
1960	1.01	1.03	0.88	1.08	0.97	1.04	1.08	0.86	0.88	1.11
1970	1.07	0.96	0.99	0.89	0.97	0.99	0.97	0.97	1.09	1.00
1980	0.94	1.04	0.89	1.13	0.89	0.80	1.13	1.04	0.93	0.85
1990	1.04	1.00	0.75	0.95	1.04	0.96	1.00	0.95	0.92	1.09
2000	1.05	1.04	0.96	1.04	0.79					