Radial growth-climate association of *Thuja occidentalis* L. at the northwestern limit of its distribution, Manitoba, Canada

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Abstract

Radial growth of *Thuja occidentalis* at the northwestern limit of its distribution in Manitoba, Canada was negatively correlated with temperature during the late summer months of the year prior to ring formation. It was also positively correlated with precipitation and negatively correlated with temperature during the early summer months of the year the annual ring was formed. This suggests early summer water balance limits the growth of *T. occidentalis* in this area. Our result also showed a positive correlation between *T. occidentalis* radial growth and warm late fall temperature. It is speculated that temperature may be related to the limit of distribution of the species. However, the biological processes involved are not understood. Except for the influence of late fall temperature, the radial growth-climate association of *T. occidentalis* in Manitoba does not differ much from those reported from other portions of its range.

Keywords: northern white cedar, radial growth, late fall temperature, response function, dendrochronology

Introduction

*T. occidentalis* reaches the northwestern limit of its distribution in Manitoba, Canada. Disjunct populations occur in the Cedar Lake area. These isolated outliers, known by the First Nations, were important in the days of the fur-trade as a source of cedar bark for the repair of canoes on the long voyage between the northwestern posts and York Factory (Scoggan 1957). The presence of *T. occidentalis* on the shores of Cedar Lake was mentioned during the travel and adventures of fur trader Alexander Henry, i.e., between the years of 1760 and 1766 (Henry 1901). Later, in the geological and natural history survey of Canada (1879-1880) this isolated population was qualified as a remarkable outlier (Selwyn 1881). It was noted that a population of *T. occidentalis* was found 190 miles (~306 km) to the northwest of its large continuous distribution on the shores of Lake Winnipeg.

The ability of northern white cedar (*Thuja occidentalis* L.) to reach an extremely old age has been documented in many studies (Sheppard, Cook 1988; Larson, Kelly 1991; Archambault, Bergeron 1992ab; Kelly et al. 1994). While it was suggested that *T. occidentalis* offers great potential in the field of dendroclimatology, little of its range has been sampled by dendrochronologists (Sheppard, Cook 1988). The possibility of finding old *T. occidentalis* trees growing at the extreme limit of their distribution and constructing a multi-century-long tree-ring chronology has motivated this study. Our objective was to investigate the radial growth–climate association of *T. occidentalis* at its northwestern limit. This species is usually found in areas where normal average January temperatures range from -4°C to -12°C (Burns, Honkala 1990). Meteorological data from the nearby Grand Rapids Hydro station indicates, however, that the mean January temperature for the period 1966-1990 was -19.8°C (Environment Canada 1993). We therefore hypothesized that cold winters would limit radial growth of *T. occidentalis* trees. In addition, *T. occidentalis* is known to grow well in areas where annual precipitation ranges from 710 to 1170 mm and is also found in areas with precipitation of 510 mm, i.e., at the northern and western limits (Burns, Honkala 1990). Data from the Grand Rapids Hydro station indicates that for the period 1961-1990 the mean annual precipitation was 483.4 mm (Environment Canada...
We therefore hypothesized that, in addition to cold winters, insufficient precipitation in the summer limits radial growth of *T. occidentalis*.

**Methods**

**Study Area**

The study area is located in the region surrounded by Lake Winnipegosis, Cedar Lake and Lake Winnipeg about 390 km northeast of Winnipeg, Manitoba (Fig. 1). More precisely, the area is located on The Pas end moraine, one of the largest in Manitoba, which extend from the town of The Pas south and east to just south of Grand Rapid (Teller 1975). In this area, several disjunct populations of *T. occidentalis* occur on beach ridges and bogs. Both habitats were sampled. In the area, *T. occidentalis* is often associated with black spruce (*Picea mariana* Mill.), white birch (*Betula papyrifera* Marsh.), willows (*Salix* spp.) and eastern larch (*Larix laricina* (Du Roi) Kock.) (Weber, Bell 1990). In our area, hydric sites supported *P. mariana* while beach ridges supported mixed hardwood species.

The nearest meteorological station is at Grand Rapids Hydro (53°09’N, 99°17’W) within ca. 40 km of our sites (Fig. 1 and Tab. 1). The mean annual temperature and total precipitation are, respectively, 0.5°C and 483.4 mm for the period 1966 to 1990. The mean temperature reaches a high of 18.8°C in July and a minimum of -19.8°C in January. About 76% of the total annual precipitation occurs as rainfall (Environment Canada 1993).

**Sampling and chronology development**

*T. occidentalis* were sampled from many sites along an east-west transect starting from Long Point, Lake Winnipeg (Fig.1). Two cores were extracted from living trees except for those having heart rot. Twelve cross-sections were also collected from stumps. All cores and cross-sections were prepared following standard methods. After visual cross-dating (Stokes, Smiley 1968) of the cores, ring-widths were measured at a precision of 0.001 mm using a Velmex measuring system. Our first step was the creation of an error-free chronology based solely on information obtained from cores. Once this chronology was constructed, program COFECHA (Holmes 1992) was used to assign a date to the cross-sec-

![Fig. 1 - Location of the study area, the sampled sites and of the meteorological stations. The black squares indicate the sampling sites and the letters indicate the meteorological stations: A) Berens River, B) Channel Island, C) Grand Rapids and D) Norway House.](image)
tions. These dates were verified by visual cross-dating. In all cases there was sufficient overlap to match the unique patterns of ring-widths. Samples taken from stumps strengthened the time series and greatly increased the time span. Ring width values for each series were then graphed and periods of anomalous suppression or release from growth were eliminated and the series split (Blasing et al. 1983). Data quality was further validated with program COFECHA and series that were poorly correlated with the average chronology were rechecked and either corrected or eliminated.

To extract the age-related trend and the non-climatic signal, each measurement series was standardized using a spline function with a 50% frequency response of 53 years (Cook, Peters 1981). The flexibility of the spline function was justified by the need to eliminate low frequency variations related to stand dynamics (close canopy trees often with fire scars) but to maintain decadal fluctuations related to climate. Autoregressive modelling was performed on each standardized series to remove temporal autocorrelation. To diminish the effect of endoge-nous stand disturbances and to enhance the common signal, all residual series were averaged using a biweight robust mean. These procedures were conducted using program ARSTAN (Cook 1985). The T. occidentalis residual chronology covered the period 1713-1999 and was composed of 40 trees (69 radii) from all sampling sites.

Dendroclimatic analysis

The radial growth-climate association of T. occidentalis was investigated with both bootstrapped response function and correlation analyses (Fritts 1976; Briffa, Cook 1990). Calculations were done with the empirical model PRECON (Ver 5.16) which included a bootstrap procedure to estimate the standard error of the response function weight (Fritts et al. 1991). We conducted 999 iterations. Because of the limitations inherent in PRECON (i.e., a maximum 100-years of data), the climatic analysis was conducted for the period 1899-1998. Climatic data obtained from meteorological stations located in four locations (Fig. 1) was used

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Elev. (m)</th>
<th>Distance (km)</th>
<th>Period of records</th>
<th>Missing Data (%)</th>
<th>Mean temp. (°C)</th>
<th>Mean prec. (mm)</th>
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</thead>
<tbody>
<tr>
<td>Berens River</td>
<td>52° 21’ N, 97° 02’ W</td>
<td>217</td>
<td>176</td>
<td>T: 1905-1964</td>
<td>10.35</td>
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<td></td>
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<td>P: 1905-1964</td>
<td>8.47</td>
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<tr>
<td>Berens River A</td>
<td>52° 21’ N, 97° 02’ W</td>
<td>222</td>
<td>176</td>
<td>T: 1985-1998</td>
<td>23.21</td>
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<td>P: 1985-1998</td>
<td>24.41</td>
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<tr>
<td>Channel Island</td>
<td>52° 18’ N, 97° 23’ W</td>
<td>216</td>
<td>159</td>
<td>T: 1889-1904</td>
<td>1.56</td>
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<td>P: 1886-1904</td>
<td>2.63</td>
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<tr>
<td>Grand Rapid</td>
<td>53° 11’ N, 99° 16’ W</td>
<td>223</td>
<td>4</td>
<td>T: 1960-1979</td>
<td>27.29</td>
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<td>P: 1960-1979</td>
<td>28.75</td>
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<tr>
<td>Grand Rapid Hydro</td>
<td>53° 09’ N, 99° 17’ W</td>
<td>223</td>
<td>0</td>
<td>T: 1966-1998</td>
<td>2.02</td>
<td>1.0</td>
<td>512</td>
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<td>P: 1966-1998</td>
<td>3.03</td>
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<tr>
<td>Norway House</td>
<td>53° 59’ N, 97° 50’ W</td>
<td>217</td>
<td>133</td>
<td>T: 1897-1946</td>
<td>10.17</td>
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<td>P: 1896-1968</td>
<td>39.61</td>
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<tr>
<td>Norway House A</td>
<td>53° 58’ N, 97° 50’ W</td>
<td>223</td>
<td>132</td>
<td>T: 1973-1998</td>
<td>0.96</td>
<td>-0.8</td>
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<td></td>
<td>P: 1973-1998</td>
<td>0.96</td>
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<tr>
<td>Norway House Forestry</td>
<td>54° 00’ N, 97° 48’ W</td>
<td>217</td>
<td>136</td>
<td>T: 1970-1998</td>
<td>7.76</td>
<td>-0.2</td>
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<td>P: 1970-1998</td>
<td>7.18</td>
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Tab. 1 - Characteristics of the meteorological stations. Mean annual temperature and total annual precipitation for the common period of 1981-1990 are presented.
to compute regional monthly mean minimal-maximal temperature and total monthly precipitation for the period 1886-1999 (Tab. 1). These stations were the closest ones available and contained the longest record. Program MET from the PROGLIB library (Holmes 1992) was used to compute the regional climatic series. For each station, monthly variables were transformed into normalized standard deviation to give each station the same weight in calculating the regional average value for each month and year. When station relocation or a recording interruption occurred, the station was split and considered as different ones. To assess the validity of the monthly regional series, cross-correlations were computed with the Grand Rapids Hydro station using all available monthly data from the periods 1966-1998 (mean r for minimum temperature = 0.97, mean r for maximum temperature = 0.98, mean r for total precipitation = 0.89, all p values =0.0001). A 16-month period was used to determine the radial growth-climate association of *Thuja occidentalis*. This period was determined after Ahlgren (1957) and Forster et al. (2000) who reported that radial growth of *T. occidentalis* extended from mid-May to mid-August. When missing data occurred in the regional series, these were estimated using the mean of that month.

**Results and Discussion**

**General Statistics**

The residual chronology for *T. occidentalis* extended from 1713-1999 and is well replicated from 1850 onward (Fig. 2). A prolonged period of reduced radial growth was observed centered around 1890. This period was also reported in *P. mariana* and jack pine (*Pinus banksiana* Lamb.) trees growing in southwestern Manitoba and corresponded to a period of major forest fires (Gill 1930; Gillard et al. 2001). Other records also attest that the late 1880 - early 1890 period was extremely dry in Manitoba (Hope 1938; Allsopp 1977; Sauchyn 2000). The residual chronology displayed a mean

![Fig. 2 - A) Residual tree-ring chronology for *Thuja occidentalis* for the period 1713-1999. The number of cores included is indicated by the bottom line. The bold lines represent a 11-year unweighted running average to highlight the long-term fluctuations.](image-url)
sensitivity and standard deviation of 0.14 and 0.12 respectively. These statistics are very similar to those reported for other areas (Archambault, Bergeron 1992b; Kelly at al. 1994; Tardif, Bergeron 1997; Case 2000). The same was observed for the mean correlation among all radii (0.27) and the percentage of variance explained by the first eigenvector (30.4%). These results suggested that radial growth of *T. occidentalis* at its limit of distribution may not be strongly limited by climatic factors. This is further stressed by the near absence of missing ring (0.03%). However, *T. occidentalis* appears to be a good indicator of climate anomalies leading to extended drought periods. In a dendroclimatic reconstruction of precipitation using *T. occidentalis* trees from our region, Case (2000) also reported periods of dryer years in the 1790s, 1840s, 1890s and 1930s.

**Radial growth - climate association**

The bootstrapped response function calculated for the period 1899-1988 and using maximum temperature explained more variance in the species residual chronology than when using minimum temperature (Fig. 3) or mean temperature (not shown). The good fit of the models was further illustrated in Figure 4 which showed *T. occidentalis*’ residual chronologies and the estimated series developed from the statistical model. Radial growth of *T. occidentalis* was negatively correlated with maximum August temperature of the year prior (t-1) to ring formation (Fig. 3). This suggests that water stress could lower the accumulation of carbohydrate reserve, a situation deleterious to growth in the following year. Similar results were reported by Archambault and Bergeron (1992b), Kelly et al. (1994), Tardif and Bergeron (1997) and Case (2000). For the Niagara escarpment, Kelly et al. (1994) also reported a negative association with radial growth of *Tsuga canadensis* near its northern range limit (Tardif et al. 2001). The processes by which late fall temperature may influence radial growth of *T. occidentalis*, however, are not understood. A first hypothesis may relate to desiccation and structural damage to needles and buds. Cold resistance processes may be involved because deep dormancy is important to enhanced winter survival (Havranek, Tranquillini 1995) although *T. occidentalis* is reported to have a high resistance to frost (Sims et al. 1990). Dessication injury (winter-drought injury) in *T. occidentalis* was reported by Curry and Church (1952). Another hypothesis may relate to the fact that mild late falls may reduce the depth to which the soil is frozen, thus allowing for an earlier resumption of photosynthesis in the spring and a longer growing season.

Our result indicated that *T. occidentalis* may take advantage of an earlier growing season. This has been reported for many conifer species (Graumlich 1993; Holfgaard et al. 1999; Tardif et al. 2001; Tardif et al. 2002). Our results showed that radial growth was negatively correlated to March precipitation. In our area, snow represents 86% of March precipitation. Heavier snow accumulation may delay the resumption of photosynthesis and *T. occidentalis* is also reported to be susceptible to snow and ice damage (Burns, Honkala 1990). April-May maximum temperatures were positively correlated to radial growth and this was also observed by Kelly et al. (1994). As mentioned by Cook and Cole
(1991), above-average temperatures could improve the thermal conditions by quickly removing snow cover and by allowing for an earlier-than-normal resumption of photosynthesis.

Finally, radial growth of *T. occidentalis* was negatively correlated with June maximum temperature of the year the annual ring was formed (t) and positively with June-July precipitation (t). This refers to the classical moisture stress response and suggests that water balance during the early growing season influences radial growth. Growth conditions in June are especially important because, in *T. occidentalis*, 70-80% of the ring may be produced by the end of June (Bannan 1955). The same association was...
observed in Northern Québec by Archambault and Bergeron (1992a) and Tardif and Bergeron (1997). For the Niagara escarpment, Kelly et al. (1994) have reported a negative correlation with June maximum temperature but no correlation with June precipitation or any other month.

**Conclusions**

This study has documented the climatic response of *T. occidentalis* at the northwestern limit of its distribution. Our results indicated that the climate conditions prevailing in the late summer prior to the ring formation and those occurring in June and July of the year the annual ring is formed are determinants for radial growth of *T. occidentalis*. This was also observed in other studies. In contrast, the positive association with warm late falls and its possible relation with the northwestern limit of distribution of the species merits further attention. The low mean sensitivity as well as low correlation coefficients reported suggest that climate does not strongly limit radial growth of *T. occidentalis* at its northwestern limit. Climate could, however, influence sexual reproduction and seedling establishment. Future studies of *T. occidentalis* stand dynamics may reveal that other factors, like forest fires or habitat availability, are responsible for the present distribution of the species. Many *T. occidentalis* trees bearing fire scars were observed and it may be that the fire regime in the Cedar Lake area allows for *T. occidentalis* to maintain itself. Finally, the ability of *T. occidentalis* to record prolonged drought periods also accents the potential of this species for climatic reconstruction.
Acknowledgments

We thank Daniel Bailey for his help during the field sampling and Dr. Danny Blair for his assistance with the climatic data. We are grateful to Dr. Malcom Cleveland and an anonymous reviewer who made constructive comments on an earlier draft of this manuscript. This project was financially supported by the Natural Sciences and Engineering Research Council of Canada and the University of Winnipeg.

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