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Dendroclimatology of yellow cedar (Callitropsis nootkatensis) in the Pacific Northwest of North America

Christopher S. Robertson
Western Washington University

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Dendroclimatology of Yellow Cedar (*Callitropsis nootkatensis*) in the Pacific Northwest of North America

By

Christopher S. Robertson

Accepted in Partial Completion

of the Requirements for the Degree

Masters of Science

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MASTER’S THESIS

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Date: ________________________________
Dendroclimatology of Yellow Cedar (*Callitropsis nootkatensis*) in the Pacific Northwest of North America

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Masters of Science

By
Christopher S. Robertson
September 2011
ABSTRACT

As the oldest known conifer species in the Pacific Northwest (PNW), yellow cedar (Callitropsis nootkatensis (D. Don) (Spach)) represent an underexploited paleoclimate resource of significant dendroclimaticological value. This is the first dendroclimaticological study of high elevation yellow cedar within the North Cascades of Washington. In addition, I explored the coherence of yellow-cedar chronologies at the regional scale. I established master tree-ring chronologies and radial-growth characteristics of 50 high-elevation yellow cedars from four sites along the west slope of the North Cascades. Significant ($p<0.05$) mean inter-series ($\bar{r}=0.61$) and inter-site ($\bar{r}=0.75$) correlations in radial-growth pattern revealed a common limiting factor to yellow-cedar growth within the region. Correlation ($r=0.23-0.54$) between PRISM climate data and the master chronologies indicated that summer minimum temperatures were the dominant limiting factor of growth for North Cascades yellow cedar. By expanding the sample area to include yellow-cedar chronologies from Mount Rainier WA and Vancouver Island BC, I showed a significant shared pattern of radial growth between these regions. In order to determine the influence of multi-decadal climate forcings associated with the Pacific Decadal Oscillation (PDO), I constructed an averaged PNW tree-ring chronology. Correlation analysis detected the influence of the PDO throughout the chronology. Wavelet analysis revealed the low-resolution (150-250 year) influences of temperature across the regional chronology and significant suppressed growth at all sites in response to stratospheric volcanic eruptions during the 1810’s. Further sampling and the inclusion of yellow cedar in multi-proxy reconstructions could improve scientific understanding of paleoclimate in the PNW.
ACKNOWLEDGMENTS

I would first like to thank my advisor Dr. Andy Bunn for his tireless support and edits throughout this project, his guidance and mentoring have honed my skills as a scientist and helped make me into the professional that I am today. I would like to thank the members of my thesis committee, Dr. Andrew Bach for his constant encouragement and advice, and Dr. Michael Medler for his support and edits. I would also like to thank Dr. Jeremy Littell for his field/lab support, as well as Dr. Colin Laroque and Ailene Ettinger for their data contributions to this work. This project would not have been possible without the field support of Logan Burner, Tyler Llewellyn, Holly Faulstich, Greg Stone, Jena Christiansen, Alex Westcott, Brenna Forester, and Jody Gerdts. Lastly, I would like to thank Chandler Stone for his edits and Gretchen Robertson for her unending support and editorial skills without which this project would not be possible.
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1. BACKGROUND

The Pacific Northwest region (defined here as Oregon, Washington, and southern British Columbia, and abbreviated hereafter as PNW) represents a unique and rich biome of significant ecological, cultural and economic importance (Franklin and Dyrness, 1983). Perhaps the most defining characteristics of this region are its unique biodiversity and biogeography stemming from a complex climate system driven by the Pacific Ocean. Variability in the PNW climate system plays a significant role in the biogeography of this region and has been linked to increases in the severity and frequency of disturbances, widespread vegetation loss and significant impacts on fisheries (Hennon et al., 2008; Littell et al., 2010; Mantua et al., 1997). With projections of heightened climatic variability, understanding the mechanisms behind, and responses to, a changing regional climate is of growing interest to natural resource managers, conservationists and policy makers (IPCC Working Group 1, 2007).

Current knowledge of past climates of the PNW is relatively vague and predominately limited to the instrumental record (1890-present) (Leung and Ghan, 1999). A strong grasp of pre-instrumental climates within a region can often be obtained through climatologically sensitive tree-ring chronologies. While dendrochronological resources are prevalent throughout the PNW, most tree species lack the temperature-sensitive qualities necessary to achieve a clear understanding of pre-instrumental climates and their effects on terrestrial ecosystems (Peterson, 2002). The most sensitive and long-lived species with these characteristics (e.g. bristlecone pine *Pinus longaeva*) commonly grow under extreme conditions in cold and dry regions (Salzer et al., 2009). The environment of the PNW does
not typically provide many species that fit these criteria. Thus, developing new paleoclimate resources are an essential key to unlocking the paleoclimate of the PNW.

Yellow cedar (Callitropsis nootkatensis (D. Don) (Spach)) is a plausible resource for PNW paleoclimate data. Yellow cedar has been referred to as Alaska yellow cedar, Nootka cypress, and Alaska cypress. While this species is a cypress, its true taxonomy has been under scrutiny and has been formerly known as Chamaecyparis nootkatensis, Cupresses nootkatensis and Xanthocyparis nootkatensis. This mixed taxonomic background is largely due to there being very few genetic relatives found throughout the globe (Hennon et al., 2008). Yellow cedar is the hardest of the known cedar species and exceptionally resistant to rot and insect making it a highly desired wood product. This species is also of significant cultural importance to First Peoples in the PNW (Turner et al., 2000).

1.1 Scope of Research

The goal of this research was to investigate the dendroclimatological viability of yellow cedar within the North Cascades sub region and the greater PNW. By building upon the previous success of yellow-cedar tree-ring studies on Vancouver Island BC (Laroque and Smith, 1999) this research aimed to expand upon the yellow-cedar dendrochronological network in an attempt to exploit unexplored Washington State distributions of this species. This work was different from past studies in two ways:

- This was the first dendroclimatological investigation into North Cascades yellow cedar.
- This was the first look into the role of the PDO in the regional radial-growth of high elevation yellow cedar.
1.2 Objectives

- I quantified patterns in radial growth within and between stands of North Cascades yellow cedar, identified the climate variables associated with those patterns and determined limiting factors to growth.

- I quantified shared patterns in radial growth between the North Cascades, Vancouver Island and Mount Rainier sub-regional chronologies, identified the spatial and temporal role of broad scale atmospheric forcings (i.e. PDO) and broad scale disturbances (i.e. volcanism) in those patterns and determined regional radial growth response.

1.3 Organization

Both research chapters of this work were designed as individual, stand-alone studies. Chapter one explores the dendroclimatological potential of North Cascades yellow cedar while chapter two builds upon the data from chapter one and takes a broad-scale look at yellow cedar throughout the PNW region. Both of these chapters are meant to stand alone, however, they both utilize North Cascades yellow-cedar chronologies.
2. **Dendroclimatology of Yellow Cedar** (*Callitropsis nootkatensis*) **on the Mesic West Slope of the Cascade Mountains in Washington State, USA**

2.1 **Introduction**

Prehistoric regional climate patterns and their effects on terrestrial ecosystems of the PNW are poorly known (Brubaker, 1986; Whitlock, 1992; Peterson and Peterson, 2002). However, current changes in temperature have been tied to widespread tree mortality and increased frequency/severity of disturbances throughout the PNW (Hennon et al., 2008; Littell et al., 2010). Understanding of the magnitude and spatial patterns at which PNW forests have and will respond to a changing climate is often partially derived from climatologically sensitive tree-ring chronologies (Peterson and Peterson, 1994). While dendrochronological resources are prevalent throughout Western Washington, they typically lack the long-lived (>500 years) and temperature-sensitive qualities necessary to achieve a clear understanding of pre-instrumental climates and their impacts on terrestrial ecosystems (Littell et al., 2009).

Tree-ring chronologies can serve as a proxy for prehistoric climates by demonstrating changes in natural variability, plant growth and severity of disturbance (e.g., fire, volcanism, insects) at inter-annual and multi-decadal time scales (Fritts, 2001). Generally the most sensitive and long-lived species that capture these data (e.g., Bristlecone pine *Pinus longaeva*) grow under extreme conditions in cold, arid regions (Salzer et al., 2009). Washington State’s wet western slope of the Cascades does not typically provide a species or sites that fit these criteria. Thus, new temperature proxies that address long timescales (>500 years) are necessary to understand the Pacific Northwest’s climate past and its future climate scenarios (Leung and Ghan, 1999). In response to this disparity, I explored the viability of yellow-
cedar (*Callitropsis nootkatensis* (D. Don) (Spach)) as a new paleoclimate resource for the west slope of the North Cascades in Washington State.

Previous research suggested that PNW yellow cedar was a poor resource for climate data. Evidence of growth asymmetries caused by buttressing and a propensity for false and missing rings stifled the use of yellow cedar as a proxy resource for nearly 20 years (Brubaker, 1980). This was not challenged until a Vancouver Island study revisited yellow cedar as a potential dendrochronological resource because of its “exceptional longevity and unsubstantiated crossdatability” (Laroque and Smith, 1999). Vancouver research selected yellow cedars with minimal buttressing and sampled above the buttress. This change of methods allowed researchers to successfully cross-date this long-lived and temperature-sensitive species, and established coastal distributions of yellow cedar as a viable and important paleoclimate resource (Laroque and Smith, 1999, Laroque, 2002). However, sampling was limited to Vancouver Island populations that only accounted for a small portion of yellow-cedar distribution. Remaining populations throughout Washington, Oregon and Northern California represent an unexploited resource for potential paleoclimate data (Hennon et al., 2008). Furthermore, North Cascades yellow cedar display consistently straight main stems with little to no buttressing.

My research explored yellow cedar as a proxy for paleoclimate data throughout the Cascade west slope of Washington State and addressed the following objectives. I quantified patterns in radial growth within and between stands of North Cascades yellow cedar; identified climate variables associated with those patterns; and determined limiting factors to growth. My initial hypothesis was that North Cascade yellow-cedar chronologies would
exhibit similar annual and decadal growth patterns regardless of their geographic position and that those patterns derived from a common limiting factor to growth.

2.2 Study Site

The maritime climate of the PNW is characterized by dry (<20 cm), warm (~25° C) summers and wet (>75 cm), cool (~7° C) winters with varying annual precipitation due to changing storm tracks and abundant orographic lifting (Franklin and Dryness, 1983). At elevations >1000 m the majority of precipitation falls as snow and is stored as snowpack until the spring melt resulting in a very short growing season. The presence of the Cascade Mountain Range modifies the large-scale climate forcings that control regional biogeography and forms a barrier to moist air masses moving east. This creates a wet temperate westerly slope and dry eastern slope (Garvert et al., 2007).

Yellow cedar is restricted to the PNW of North America ranging between coastal Alaska and northern California (Franklin and Dryness, 1983) (Fig. 1). Northern distributions of yellow cedar are prevalent in lower elevations in the coastal Western Hemlock Zone, while central and southern distributions are part of scattered stands at higher elevations.

![Figure 1. Location of study sites within the Pacific Northwest N. America. (Based on maps created by USGS)](image-url)
within the Mountain Hemlock Zone (MHZ). North Cascade yellow cedar is found in patches and mixed conifer stands at elevations >1000 m throughout the MHZ. Yellow cedar is a stress-tolerant generalist that finds its niche within the less desirable, nutrient-poor and well-drained soils in the periphery of the MHZ (Klinka et al., 1991). Stands growing within this zone are thought to be remnant disjunct populations from pre-glacial periods (Whitlock, 1992; Brooke et al., 1970).

2.3 Methods

2.3.1 Field Sampling

I selected sites through a priori geographic analysis and local knowledge of yellow-cedar stands near the upper forest border. I collected samples during the summers of 2008-2010 from four sites within the inland MHZ of the Washington Cascade west slope (Figure 1). I selected mature stands of yellow cedar from sites with similar topographic and stand characteristics at elevations >1000 m and when possible, collected at the upper elevation growth limit at each site (Table 1). At all sites I obtained a representative sample of individual trees with minimal main-stem damage. Using an increment borer, I collected a minimum of two radii from each tree at cross-slope positions near breast height (~1.4 m above ground). I recorded and photographed canopy dynamics and general understory composition for all sites. Upon completion of this work all raw measurement data will be made public on the International Tree-Ring Databank (http://www.ncdc.noaa.gov/paleo/treering.html).
2.3.2 Lab Processing

I air-dried, mounted and sanded samples to a high finish. Using a stereo microscope and Velmex sliding stage, (Velmex Inc. Bloomfield NY) I measured ring widths to the nearest hundredth of a mm. I then cross-dated each series and statistically verified them using both COFECHA and the dplR package in R (R Development Core Team, 2009; Holmes, 1983; Bunn, 2008). In an attempt to locate false and missing rings, I first visually cross-dated samples against the second core from the same tree and I skeleton plotted samples that required further investigation against the master chronology to aid the cross-dating process. I converted ring widths to dimensionless growth indices through division after fitting either a modified exponential curve or straight line to remove biological growth trends originating from tree age and stand characteristics. I built master chronologies by averaging together the index values of all samples by year. I used COFECHA to calculate three statistical variables. First, I used mean sensitivity (the difference between successive rings divided by the mean) to determine the relative year to year change in ring width. Second, I used average autocorrelation (the relationship between year \( t \) and year \( t-1 \)) to determine lagged growth response. Third, I used mean series intercorrelation (the strength of the common signal) to determine shared drivers of yellow-cedar growth. I built master chronologies for all four sites.

<table>
<thead>
<tr>
<th></th>
<th>Canyon Lake</th>
<th>Grouse Butte</th>
<th>Squire Creek</th>
<th>Mount Pilchuck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude (N)</td>
<td>48°48'43&quot;</td>
<td>48°48'54&quot;</td>
<td>48°09'46&quot;</td>
<td>48°04'15&quot;</td>
</tr>
<tr>
<td>Longitude (W)</td>
<td>122°02'10&quot;</td>
<td>121°55'41&quot;</td>
<td>121°37'32&quot;</td>
<td>121°48'37&quot;</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>1310-1402</td>
<td>1219-1341</td>
<td>1005-1371</td>
<td>944-1005</td>
</tr>
<tr>
<td>Aspect</td>
<td>NNW</td>
<td>NNE</td>
<td>NNE</td>
<td>N</td>
</tr>
</tbody>
</table>
and then averaged them together to form the North Cascades regional chronology using the methods outlined for tree-ring reconstructions by (Cook and Kairiukstis, 1990).

2.3.3 Climate and Radial Growth Analysis

I calculated time-varying correlations in pattern of growth within and between sites by determining departures from the mean over a given period using a 100-year moving window. This method removed the effect of inter-annual variability and captured the overall pattern of growth. I obtained PRISM gridded data sets of monthly surface temperatures at four kilometers resolution for the period AD 1895-2010 for comparison to tree growth at each site (www.prismclimate.org). PRISM is a spatially explicit climate dataset that uses point data from weather stations, a digital elevation model and other spatial data sets to generate gridded estimates of climate. The climate data effectively characterized mountainous areas of the western United States and included topographic-driven patterns like rain shadows and inversions (Daly et al, 2009). I correlated individual site chronologies with the PRISM climate data specific to each sample site using bootstrapped correlation analysis with the Dendroclim package in R (Biondi, 1997).

Table 2. Chronology characteristics for all four sample sites.

<table>
<thead>
<tr>
<th></th>
<th>Canyon Lake</th>
<th>Grouse Butte</th>
<th>Squire Creek</th>
<th>Mount Pilchuck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of samples</td>
<td>31</td>
<td>15</td>
<td>26</td>
<td>28</td>
</tr>
<tr>
<td>Number of trees</td>
<td>17</td>
<td>10</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Average segment length (yrs)</td>
<td>430</td>
<td>522</td>
<td>434</td>
<td>621</td>
</tr>
<tr>
<td>Range (yrs)</td>
<td>1233-2007</td>
<td>1251-2010</td>
<td>1188-2009</td>
<td>1151-2010</td>
</tr>
<tr>
<td>Length of chronology (yrs)</td>
<td>755</td>
<td>760</td>
<td>822</td>
<td>860</td>
</tr>
<tr>
<td>Mean inter-series correlation (r)</td>
<td>.69</td>
<td>.58</td>
<td>.56</td>
<td>.61</td>
</tr>
<tr>
<td>Mean sensitivity</td>
<td>0.25</td>
<td>0.24</td>
<td>0.26</td>
<td>0.22</td>
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<tr>
<td>Mean autocorrelation (r)</td>
<td>0.81</td>
<td>0.82</td>
<td>0.76</td>
<td>0.9</td>
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</table>
2.4 Results

2.4.1 Chronology Characteristics

I included a total of 100 samples from 55 trees in the master chronology that ranged in age from 755 years at Canyon Lake to 860 years at Mount Pilchuck. With an average sample length of 500 years, I found trees within all sites to be ~600-years old and found some individuals to have over 1,000 annual rings. Master chronologies displayed shared trends in growth pattern with distinct climatic episodes (e.g., Little Ice Age) (Fig. 2). The

Figure 2. North Cascades plotted master chronologies fit with a 30-years spline and truncated to a sample depth of >5.
regional chronology also displayed clear decadal and multi-decadal variability and a distinct 20th century growth trend characterized by increased radial growth that was anomalous compared to the previous 800 years in the chronology (Fig. 3). All sites expressed high mean sensitivity (0.24), high mean autocorrelation (0.82) and high mean inter-series correlation (0.61). These characteristics suggest a common site-level driver of growth (Table 2).

Significant correlations in growth pattern between sites (r=0.50-0.90 p<0.05) were also prevalent throughout all four chronologies at the 95% confidence interval (Fig. 4). These between-site correlations suggest a common radial growth pattern within the Cascades sub-region.

![Graph](image)

**Figure 4.** Correlation between regional and site level pattern of growth using a 100-year sliding window.

2.4.2 Climate Growth Association

All sites expressed significant (p≤0.05) correlations (r=0.23-0.54) with current-year winter, spring and summer (January-July) minimum temperatures with the highest correlations (>0.4) in the summer (June-July) at all sites. Canyon Lake, Grouse Butte and
Mount Pilchuck were also positively correlated ($r=0.20-0.58$) with previous year summer minimum temperature (Fig. 5). Slightly lower correlations ($r=0.20-0.37$) with current year winter maximum temperature were also present at all sites. Similar findings were present in the regional chronology, which was significantly correlated ($r=0.3-0.5$) with current winter, spring and summer (Jan-Aug) minimum temperatures as well as previous-year summer minimum temperatures (Fig. 6).

2.5 Discussion/Conclusion

There are five principal indicators that North Cascade yellow cedars share a pattern in radial growth driven by minimum summer temperatures within and between sample sites. First, the high mean sensitivity (0.24), which is a measure of between-ring variability, indicates the climatic sensitivity of the individual trees. Second, the high average
autocorrelation (0.82), which describes correlation between successive increments, demonstrates a shared pattern of growth between the individual trees (Fritts, 2001). Third, high mean inter-series correlation (0.61) determines that the shared pattern in growth derives from a common limiting factor. Fourth, significant between-site correlations (>0.5) throughout the length of all chronologies indicate a dominant regional limiting factor to growth (Fig. 4). Fifth, significant summer minimum-temperature correlations within all chronologies indicate minimum temperatures as the shared driver of growth within and between sample sites (Fig. 6). These findings support my working hypotheses of a regionally shared limiting factor to growth regardless of geographic locality. This corresponds with what is known about yellow cedar annual growth cycles.

Temperature is the limiting factor throughout the annual growth cycle of yellow cedar (Laroque, 1999; Fig. 5). Correlations with current-year winter minimum temperatures are associated with decreased snowpack leading to an earlier onset of de-hardening and an extended early wood development stage that supports radial growth (Graumlich and Brubaker, 1986) (Fig. 6). A response to changes in snowpack is common for climatically sensitive tree species within the PNW (Peterson and Peterson, 1994). Correlations with summer minimum temperatures are associated with a lengthened early wood development stage that also supports radial growth (Laroque, 1999; Peterson et al., 2002). This relationship between temperature and the annual growth cycle of yellow cedar is consistently recorded throughout my data. These findings represent a unique temperature signal within a dendroclimatological network dominated by hydrologically sensitive species.

My data augments the findings of Laroque (1999) by expanding the use of yellow cedar into the Cascades of Washington State. Previous research by Laroque (1999) used one
climate station for all climate comparisons and assumed climate heterogeneity throughout multiple sites across a large sample area. This method did not account for complex climate processes such as inversions and other site-level variables. I used the PRISM gridded data set, which accounted for local topographic-driven patterns like rain shadows and inversions (Daly et al., 2009). This method gave significantly higher climate correlations within and between all sites (data not shown). PRISM data are available throughout the remaining unexploited southern distributions of yellow cedar and provide researchers with an easily accessible and standardized climate data source for future comparisons to yellow-cedar radial growth.

This study has demonstrated that yellow cedar is a viable reconstruction grade proxy for the PNW and offers broad implications and applications for this region. First, the temperature-sensitive abilities of this species are the only of its kind within the current dendroclimato logical network of the Cascade west slope (Littell, 2010). Second, the exceptional longevity of this species expands the available tree-ring data for this region from <500 years to >700 years and with continued sampling has potential for a millennial length record. Populations throughout Washington, Oregon and California remain under-researched and represent a significant potential over unknown timescales. This proxy will not only further paleoclimate understanding of the PNW but allow for investigation into the decadal and multi-decadal forcings that drive our regional climate.

Unfortunately, further exploitation of this species could be threatened by the very climate it records. Projections of future climates within the PNW widely suggest increased summer temperatures as well as decreased winter snow pack (Littell, 2010). Both of these conditions have been tied to widespread yellow-cedar mortality within the Alaska and
Canadian distributions and suggest an increase in yellow-cedar mortality with descending latitude over time (Hennon et al., 2008). Little is known about the health of yellow cedar within its southern distributions. There is a need for further research within the Washington, Oregon and Northern California populations.

What was previously considered a viable climate proxy for only the Vancouver Island sub-region is now demonstrated as a paleoclimate resource for the North Cascades west slope and potentially the greater PNW region. Remnant stands of North Cascade yellow cedar have persisted in the margins of the Mountain Hemlock Zone for extensive periods of time (Peterson and Peterson, 2002). My discovery of a shared pattern of growth portrays a strong relationship over large spatial scales (PNW). The relationship between yellow cedar growth and temperature has a robust dendroclimatological basis within current understanding of yellow cedar annual growth cycles. My findings further establish PNW yellow cedar as a paleoclimate proxy with unexploited potential throughout its remaining populations. With further sampling researchers will obtain an understanding of PNW climate at spatial and temporal scales that have not yet been achieved in the PNW.
3. Broad Scale Atmospheric Forcings and the Regional Radial Growth Patterns of Yellow Cedar (*Callitropsis nootkatensis*) in the Pacific Northwest, N. America

3.1 Introduction

Yellow cedar (*Callitropsis nootkatensis* (D. Don) Spach) also known as Alaska yellow cedar is an underexploited climate proxy that provides regionally temperature sensitive tree-ring data at multi-centennial timescales for the PNW region. Studies in the North Cascades of Washington and Vancouver Island British Columbia established this species as a highly temperature-sensitive and long-reaching (1000+ yrs.) dendroclimatological resource (Laroque, 1999; Ch. 2). These characteristics make yellow cedar a new data source that could be used to relate the behavior and broad-scale forcings of the PNW climate past, specifically the multi-decadal climate forcing of the Pacific Decadal Oscillation (PDO).

Climate of the PNW has been demonstrated to be largely influenced by multi-decadal variability in north-pacific sea-surface temperatures known as the Pacific Decadal Oscillation (Cayan et al., 1998). Mechanisms that drive the PDO remain poorly understood and as a result, efforts to predict its shifts have failed (Schneider and Miller, 2001). Abrupt shifts in the PDO have occurred repeatedly throughout the last century with marked impacts on fisheries (Mantua et al., 1997), stream flow (Barlow et al., 2001), tree growth (Jacoby et al., 2004; Barclay et al., 1999) snow pack and glacial behavior (Peterson and Peterson, 2002). With increasing concern for future climate conditions, understanding the role of the PDO in terrestrial ecosystems is imperative (Mote and Salathé, 2010).
Current instrumental and proxy records of the PDO fail to provide a comprehensive picture of its behavior over the necessary timescales (Mantua et al., 1997). Although instrumental data have captured two 30-60 year shifts from the warm and dry positive phases to the cool and wet negative phases of the PDO, these data are limited to the last century. Instrumental records of these oscillatory shifts do not reach the timescales necessary to confirm them as the dominate PDO pattern, thus the oscillatory model of the PDO remains in question (Gedalof et al., 2002). In addition, proxy records that extend beyond the instrumental record have detected a more muted and sporadic PDO that lacks the oscillatory characteristics of the instrumental period (Biondi, 2001). With the advent of these proxy records come new concerns about the unpredictability of the PDO and its effects on PNW climate (Peterson, 2002).

While current tree-ring proxies provide evidence of PDO shifts at longer timescales, they lack temperature-sensitive qualities (Mantua et al., 1997). Tree-ring chronologies account for the majority of current PNW PDO proxy data. However, given the temperate and mesic climate of the PNW, these data remain limited to hydrologically sensitive species and thus do not capture the pre-instrumental, lower resolution, warm and cool characteristics of the PDO (Biondi, 2001). Discovering long-lived and temperature-sensitive proxies is paramount to further exploring the effects of the PDO and its shifts on the ecosystems of the PNW (Cook and Kairiukstis, 1990).

Given the lack of long-lived (>600 yrs.) temperature-sensitive species within the PNW, there has been little work focusing on the warm and cool characteristics of a changing PDO and its effect on radial tree growth. Projections of increased climate variability within the PNW and the potential for future PDO driven ecological impacts make the need for these
data acute (Allan et al., 2010). Thus, the long-lived and temperature-sensitive characteristics of PNW yellow cedar may provide a new and unique look at the prehistoric climates of the PNW and the temperature regime of the PDO at a variety of temporal resolutions.

Temperature-sensitive yellow cedar could provide a new perspective on the low resolution PDO temperature regime. Instrumental data from the PNW region indicate that the most significant difference between the warm and cool phases of the PDO is in changes to fall, winter and spring temperatures (Mote and Salathé, 2010). Generally, a warm PDO phase results in a ~0.5 °C increase in average October-May temperatures while the cool phase results in an increase of 1.3 °C in the spring and a decrease of -0.25 °C in November-December. Precipitation can vary ±10% during warm and cool phases of the PDO. As a result, the influence of the PDO drives both temperature and precipitation in the PNW (Littell et al., 2009). Obtaining proxies for both of these variables will allow for a more comprehensive understanding of the PDO.

In an attempt to shed light on the regional coherence of yellow-cedar chronologies and their response to the PDO temperature regime, my research explored the viability of PNW yellow cedar to address three objectives. I quantified shared patterns in radial growth between the North Cascades, Vancouver Island and Mount Rainier sub-regional chronologies; identified the spatial and temporal role of broad scale atmospheric forcings (i.e., PDO, volcanism) in those patterns and determined regional radial-growth response. My initial hypothesis was that PNW yellow cedar would exhibit a shared pattern of radial growth throughout the study area reflecting quasi-oscillatory forcings of the PDO as well as periods of suppressed growth in response to volcanic events. In order to test this hypothesis, I used
correlation and response analysis to illustrate statistical relationships between radial growth and broad-scale forcing.

3.2 Methods

To address the objectives outlined above I compiled three sub-regional tree-ring chronologies from the Mount Rainier WA, North Cascades WA and Vancouver Island BC areas (Fig 7). The four Mount Rainier chronologies representing yellow cedar near tree line along the south western slope were provided by A.K. Ettinger of the University of Washington. The seven Vancouver chronologies representing yellow cedar near tree line along a North/South transect of Vancouver Island were provided by C.P. Laroque PhD from Mount Allison University (Laroque and Smith, 1999). The four North Cascades Chronologies were constructed as part of this work (see chapter two for tree-core sampling and processing techniques including de-trending and chronology construction techniques). All additional chronologies were constructed using the same methods outlined in chapter 2.

3.2.1 Radial Growth Analysis
I created averaged master chronologies for all three sub regions and the region as a whole. In an attempt to remove the effect of inter-annual variability and capture the overall pattern of growth, I calculated within and between-site correlations in growth pattern using a 100-year sliding window. This method provided time-varying correlations by calculating departures from the mean over a given window. I used a wavelet analysis (which decomposes a time series into time-frequency to illustrate variability in frequency and strength of frequency) to determine modes of variability throughout the chronologies (Torrence and Compo, 1998). I performed all statistical analysis using dplR package in R and I calculated correlations using Pearson’s product-moment correlation coefficients (R Development Core Team, 2009; Holmes, 1983; Bunn, 2008). I used COFECHA to calculate the 1) mean sensitivity (the difference between successive rings divided by the mean) to determine the relative year to year change in ring width, 2) average autocorrelation (relationship between year $t$ and year $t-1$) to determine lagged response and 3) mean inter-series correlation (strength of the common signal) to determine shared drivers of yellow-cedar growth.

3.2.2 Analysis of Broad Scale Forcings

I obtained the PDO index produced by (Mantua et al., 1997) and a 1000-year reconstruction of the PDO derived from hydrologically sensitive *Pinus flexilis* tree-ring chronologies from California and Alberta BC for comparison to yellow-cedar growth over the period of 1300-1996 (MacDonald and Case, 2005). In order to extract low-resolution variability by removing higher resolution inter-annual signals, I filtered sub-regional and regional chronologies at 25-years using a cubic smoothing spline. I correlated filtered chronologies with the PDO index using the autocorrelation function (acf) and the cross-
correlation function (ccf) in R to determine lagged responses to the PDO. In order to
determine changes in correlation over time, I examined the chronologies over three periods
(1300-1530, 1530-1760, and 1760-1996) and over each individual master chronology.

I used Superposed Epoch Analysis (SEA) to determine the influence of volcanic
events on radial growth. The SEA function calculated the significance of a departure from
the mean for a given set of event years and lagged years (Lough and Fritts, 1987). I selected a
set of 10 known volcanic event years (1600, 1641, 1665, 1674, 1680, 1809, 1815, 1823,
1835, 1883) using parameters defined by (Salzer and Hughes, 2007) for the time period
1600-1890. I chose eruption years that displayed sulfate deposits in ice cores from both poles
and had a Volcanic Explosive Index (VEI) of ≥ 5. To determine the event year’s growth
response, I used an 11-year window for the five years before the event and five years after.

Table 3. Chronology characteristics of all three sub-regional master chronologies.

<table>
<thead>
<tr>
<th></th>
<th>Mount Rainier</th>
<th>North Cascades</th>
<th>Vancouver Is.</th>
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<tbody>
<tr>
<td>Number of samples</td>
<td>162</td>
<td>100</td>
<td>359</td>
</tr>
<tr>
<td>Number of trees</td>
<td>81</td>
<td>50</td>
<td>170</td>
</tr>
<tr>
<td>Average segment length (yrs)</td>
<td>191</td>
<td>498</td>
<td>241</td>
</tr>
<tr>
<td>Range (yrs)</td>
<td>1633-2009</td>
<td>1151-2010</td>
<td>798-1997</td>
</tr>
<tr>
<td>Length of chronology (yrs)</td>
<td>377</td>
<td>860</td>
<td>1200</td>
</tr>
<tr>
<td>Mean inter-series correlation (r)</td>
<td>.53</td>
<td>.45</td>
<td>.32</td>
</tr>
<tr>
<td>Mean sensitivity</td>
<td>0.23</td>
<td>0.24</td>
<td>0.26</td>
</tr>
<tr>
<td>Mean autocorrelation (r)</td>
<td>0.79</td>
<td>0.84</td>
<td>0.71</td>
</tr>
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3.3 Results

3.3.1 Pattern of radial growth

I included a total of 620 samples from 301 trees in the PNW master chronology
representing the Mount Rainier, North Cascades and Vancouver Island sub-regions (table 3).
All chronologies displayed shared patterns in radial growth with distinct climate episodes
well represented (Fig 8). Sub-regional chronologies expressed high mean inter-series
correlation (0.31-0.53), mean sensitivity (0.23-0.26) and mean autocorrelation (0.71-0.84).
There was little difference (~0.02) between the mean inter-series correlation, mean sensitivity
and mean autocorrelation for all three sites. Significant correlations in growth pattern
between sub regions (r=0.50-0.90 \( p < 0.05 \)) were also prevalent throughout all three
chronologies at the 95% confidence interval (Table 3). Visual inspection of the 800 year old
regional chronology suggested the existence of characteristic radial-growth trends. Wavelet
analysis confirmed this by highlighting modes of variability in all chronologies at the 120-
250 year frequency while the North Cascades, Vancouver Island and regional chronologies
all expressed a mode of variability at the 30-60 year frequency. All four chronologies
displayed a single 8-10 year event at the year 1810 characterized by anomalously suppressed
growth.

Figure 8. PNW regional chronology (black) fit with a 30-year spline (red) and a dashed black
line representing sample depth.
Figure 9. Plotted master chronologies (black) with a 20-year spline (red) and Morlet continuous wavelet transform.
Figure 10. Plotted PDO (MacDonald and Case, 2005) (black) regional and sub-regional master chronologies (red) (right column) with cross-correlation analysis result over four time periods (left column).
3.3.2 Forcings

The regional chronology expressed a consistently negative correlation (>-0.4) with the PDO throughout the chronology. This agrees with other tree ring chronologies throughout the region (Mantua et al., 1997). Sub-regional chronologies expressed a mixed response to the PDO. Both the Vancouver Island and Mount Rainier chronologies had significantly negative correlations (-0.2 -0.6) with PDO in all four time windows. The North Cascades chronology expressed a mix of both negative and positive correlations throughout the four time periods (Fig 10).

SEA analysis confirmed findings of the wavelet analysis by connecting the anomalously suppressed growth over a 10-year period in the 1815’s to the eruption of two well documented stratospheric volcanic eruptions, an eruption of unknown origin in 1809 and the Tambora eruption of 1815 (Fig 11) (Cole-Dai et al., 2009).

3.4 Discussion/Conclusion

The discovery of a shared pattern of radial growth across the entire sample area and the significant negative correlation between that pattern and the PDO represent a substantial and new paleoclimate archive for the PNW region. All three sub-regional chronologies express this pattern within and between sub-regions based on three principal indicators. First,
the high average autocorrelation of 0.78 within the sub regions depicts a shared pattern of growth between the individual sample sites. Second, the high mean inter-series correlation of 0.44 indicates a shared limiting factor of growth. Third, significant correlations (0.4 - 0.9) in pattern of growth between sub-regions indicate a regional limiting factor to growth (Table 3). These findings support my initial hypothesis of a regional shared pattern of radial growth and provide strong evidence for the uniformitarianism principal in yellow-cedar tree ring/climate response throughout the PNW.

A shared pattern of radial growth over such a large spatial scale is a substantial addition to the PNW dendroclimatological network and suggests the presence of regional-scale climate forcings. A wavelet analysis helped expose these forcings as two different modes of variability at 150-250 and 30-60 years and a common single event at 8-16 years. All three of these modes of variability signify unique forcings within the yellow cedar pattern of growth and substantiate yellow cedar as a viable dendroclimatological resource.

First, temperature is the dominant driver of yellow-cedar ring-width variability at the regional scale, this supports the hypothesis of temperature driven yellow-cedar growth outlined in Chapter 2 and extends it to the regional scale. The regional chronology expressed consistent radial-growth trends at the 150-250 year frequency. Modes of variability at this interval are indicative of a temperature-sensitive species responding to the low-resolution fluctuations in regional temperature (Fritts, 2001). Of note, there is a clear stop in this mode of variability at the year 1440 marking the transition between the Little Ice Age (1440’s-1850’s) and the Medieval Warm Period (pre-1440’s) (Fig. 8). Temperature sensitive yellow-cedar chronologies in conjunction with previously established chronological networks (i.e.
*Tsuga mertensiana*) could provide a more comprehensive understanding of the temperature and precipitation patterns of the PNW over expanded timescales.

Second, the wavelet analysis displayed periodic modes of variability at the 30-60 year frequency within the regional chronology that coincide with the generally accepted 30-60 year quasi-oscillatory forcings of the PDO (Biondi et al., 2001; Gedalof and Smith, 2001). This is supported by the significant negative correlations between the PDO and the regional chronology (Fig. 10). These findings illustrate a unique relationship between increased PDO variability and increased ring-width variability. During sections of extreme PDO variability (1400-1600, 1680-1740, 1800-1996) the yellow-cedar regional chronology exhibits corresponding highly suppressed or highly increased radial growth. During periods when the PDO remains close to the mean (1600-1680, 1740-1800) the regional chronology does the same (Fig 10). The connection between the severity of the PDO and yellow-cedar radial growth indicates a relationship of strong dendroclimatological importance over large spatial and temporal scales.

Negative correlation between the PDO and yellow-cedar pattern of growth suggests a relationship between the PDO and yellow-cedar annual growth cycle. Given that the PDO reconstruction used in this study was derived from hydrologically-sensitive trees that were positively correlated with the PDO, it follows that the temperature sensitive yellow cedars display correlations of the opposite sign. This coincides with what is known about yellow-cedar annual growth cycles and exemplifies yellow cedar's ability to capture PDO climate forcings. For instance, the cool/wet negative PDO leads to a more persistent snowpack and a shortened growing season thus suppressed yellow-cedar growth, while in hydrologically-sensitive species the wet characteristics of a negative PDO lead to increases in precipitation
promoting annual radial growth. In contrast the warm/dry positive PDO leads to a less persistent snowpack and prolonged yellow-cedar growing season while the dry characteristics of this phase produce water stress for the hydrologically sensitive species. This connection between the yellow-cedar annual growth cycle and the PDO temperature regime validates the uniqueness of the yellow-cedar growth/climate relationship at the regional scale.

Lastly, the single event at the 8-16 years frequency was found in all chronologies and was characterized by a significant decrease in radial growth over a 10-year period during the 1810’s. SEA analysis revealed that this event coincides with an unspecified stratospheric volcanic eruption in 1809 followed by the Tambora volcanic eruption in 1816 these events have come to be known as the “mini ice age” or the “year without a summer” (Briffa and Jones et al., 2001). This event was found in all sample sites throughout the PNW region and can now be used as a marker event for cross-dating and expansion of the yellow-cedar dendrochronological network.

Although correlations in pattern of growth were strong throughout the regional chronology there were areas within the sub-regional chronologies where correlations dropped. Drops in correlation at the sub-regional level are likely due to changes in storm tracking caused by PDO influenced shifts in the jet stream north and south throughout the sample area. This would result in variability in PDO response between sub regions over time and would maintain a significant relationship at the broader regional scale. Of note, the North Cascades chronology displays a strong 20th century warming trend characterized by a significant increase in radial growth over the last 50-years. Both the Mount Rainier and Vancouver Island chronologies display suppressed radial growth over this same time period.
This disparity in pattern of growth is likely the cause of site-level forcings and microclimate characteristics and do not deter from the unique regional forcing of the PDO on PNW yellow cedar.

The inclusion of yellow cedar in multi-proxy reconstructions will strengthen future research given its unique temperature signal and exceptional longevity over a large latitudinal gradient. These data fill a temporal and spatial gap in the dendroclimatological network available for this region while providing a unique look at the various modes of variability associated with the PDO. Past growth response to decadal temperature variability in the PDO may also provide the best indicator of the terrestrial response to future climate change. Further sampling of this species relies heavily on the ability to find them given that yellow cedar only represent <10% of the PNW canopy are the oldest tree species in the region and they exemplify a rare climate signal from an uncommon species that is of significant dendroclimatological importance.

4. SUMMARY/CONCLUSION

The goal of this research was to explore the dendrochronological and dendroclimatological potential of yellow cedar within the North Cascades sub-region and the PNW as a whole. To achieve this goal, tree-ring chronologies from the North Cascades, Mount Rainier and Vancouver Island were used to describe response to climate variables over varying spatial and temporal scales; determine patterns in radial growth within and between sample sites; and demonstrate the relationship between broad scale atmospheric forcings and the regional radial growth trends of yellow cedar. The results of this analysis indicate that North Cascades yellow cedar have an untapped potential as a proxy for temperature over previously unexplored timescales for this region. The discovered shared
regional pattern of growth expresses the influence of the PDO and volcanic forcings throughout the sample area.

Chapter 2 revealed the temperature sensitivity and exceptional longevity of North Cascades yellow cedar. This investigation was designed to explore dendroclimatological potential and consistency in growth pattern within and between sample sites. These data represent the only temperature proxy of its kind for this region and therefore are an important addition to future multi-proxy reconstruction. The exceptional longevity of this species also sets it apart from current dendrochronological networks within this region. Further sampling within this region and across the elevation gradient of the yellow-cedar niche could shed light on the forcings that define the niche edge of this species (i.e., competition, precipitation), as well as produce an even longer-reaching regional chronology.

Chapter 3 displayed the regional coherence of yellow-cedar radial growth and the presence of lower resolution forcings within those patterns. With a total of 15 chronologies spanning from northern Vancouver Island south to Mount Rainier, the yellow-cedar regional network displayed uncanny coherence in its patterns of growth and further supported the dendroclimatological potential of this species outlined in chapter 2. Significant negative correlation between the PDO and yellow-cedar radial growth illuminated a relationship between periods of increased ring-width variability and energetic PDO shifts. Expansion of the yellow-cedar dendroclimatological network to include the remaining Washington, Oregon, and California distributions could provide hitherto unattained regional temperature data and a base datum for improvements in PNW paleoclimate research.

Yellow cedar was previously established as a paleoclimate proxy for Vancouver Island. This work has expanded that network to include the North Cascades and
demonstrated the dendroclimatological potential of this species at varying timescales. Unexploited populations of yellow cedar throughout the remaining southern reaches of its distribution represent an untapped potential for dendroclimatological data.
References


