Response of Tree Ring Growth to Various Climatological Indices in the Sierra Nevada

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Introduction

Tree-rings as archives of paleoclimate information have several advantages over other natural archives: they have wide geographical distribution, are easily accessible, provide accurate annual to seasonal resolution, and absolutely dated chronologies now exist for the last 12,460 years (Friedrich et al., 2004). Networks of tree-ring measurements exist for the last two millennia although replication decreases back through time (Hughes, 2002). Trees in temperate zones act as excellent high resolution proxy archives and have proven critically important for evaluating the climate history of regions with few and/or relatively short climate records and for documenting climate variability at multi-centennial and millennial timescales (Briffa, 2000). Significant contributions to paleoclimatology within the last decade have firmly established tree-rings as a valuable source of proxy data for evaluating long-term climate variability/trends, and as useful tools for developing long-term records of extreme climatic events (Briffa et al. 2004; Martinelli 2004).

The science of tree-ring dating, known as dendrochronology, uses the presence of annual rings in tree stems to date precisely past events (i.e. climate, fire, insect outbreaks) (Fritts, 1976). New growth in trees takes place in the vascular cambium by adding layers of cells to the sapwood surface (Fritts, 1976). Trees in temperate zones have annual periods of growth and dormancy related to cold weather (Smith, 2008). In conifers, layers of relatively large, less dense, thin-walled cells (early wood) are laid down early in the growing season and layers of narrower, denser cells, exhibiting thicker walls (latewood) are laid down later in the growing season (Fritts, 1976; Schweingruber, 1988) (Figure 1). The anatomical and color contrast between the early wood and latewood boundaries can be seen in a stem cross section as a series of concentric tree-rings. Many species of trees in temperate zones produce one growth ring each year, with the outer-most ring adjacent to the bark (Fritts, 1976).

![Figure 1: Successive tree-rings exhibiting early wood, latewood, and annual growth, also examples of periods of low (narrow rings) and high (wide rings) growth.](image-url)
The radial width of the rings varies from year to year, creating patterns of variation that are present across different trees in a geographical region. For example, wider rings in high growth years and narrower rings in poor growth years (Figure 1). This pattern can be visually matched (cross dated) between trees to produce precisely dated tree-ring chronologies (Stokes and Smiley, 1968).

Dendroclimatology is a sub-discipline of dendrochronology and studies the relationships between the annual growth of trees and climate (Fritts, 1976). Trees respond to climate, insect predation, fire, and other environmental disturbances with corresponding changes in their annual growth rings, a record is retained in tree-rings that can be examined using dendrochronological techniques (Fritts, 1976). However, it is a tree’s ability to act as a natural archive at spatial scales of a few hectares to hemispheres and temporal scales lasting from a few hours, such as an intense storm, through decades of drought, to centuries of changed global atmospheric circulation that is unique among natural archives (Hughes, 2002). Paleoclimatology uses the relationship between tree growth and climate variability to reconstruct past climate; this is possible because the technique is based upon the assumption that the relationship between tree growth and climate has remained unchanged over recent millennia, this is known as the, “principle of uniformitarianism” (Lyell, 1837; Fritts, 1976; Briffa et al., 1992). By measuring these characteristics in consecutive tree-rings it is possible to produce annually resolved time series that are correlated to the climate of the growing season (Fritts, 1976; Schweingruber, 1987; McCarroll et al., 2003). The dendroclimatic study of the relationship between tree-ring growth and climate is primarily empirical; instrumental data of climate variables and tree growth are calibrated and verified over a common period, this relationship is then used to estimate climatic variables prior to the instrumental period and reconstruct past climate (Fritts, 1976; Briffa et al., 1995). The strengths of dendroclimatology are the accuracy and precision with which tree-rings are measured; rigorously calibrated and tested against instrumental records on a spatial scale and to an extent that is unique among natural archives (Hughes, 2002). Recent paleoclimate reconstructions have utilized tree-rings, taking advantage of the wide range of sites and species available to contribute to our understanding of the Earth’s temperature history (Jones et al. 1998, Mann et al., 1998; Mann et al 1999; Crowley and Lowery, 2000; Huang et al., 2000; Briffa et al., 2001; Esper et al., 2002; Mann and Jones, 2003; Moberg et al., 2005; Oerlemans, 2005; Hegerl et al., 2006).

Two sites were selected in the Sierra Mountains of Northern California in order to investigate the key climatological factors that influence tree growth, with a particular interest on meteorological drought
conditions and how associated climatological factors affect growth. To analyze this we focus on two periods of drought, 1986 to 1992 and 2012 to 2017. For the first drought period, we analyzed the years 1986 to 1993 in order to determine tree-ring response to drought conditions. For the second drought period we looked at the years 2010 to 2014, while prior to the end of the most recent drought our tree rings samples were collected in 2014. Droughts, especially severe events like the 2012 to 2017 drought, can have substantial economic, agricultural, hydrological, and ecological consequences. The most recent drought was particularly devastating, Griffin and Anchukaitis refer to this drought as “exceptional” and mention that extreme aridity from 2012 to 2014 even surpassed various other droughts (Griffin and Anchukaitis 2014). Due to the harsh consequences of drought we find it essential to understand the complete scope of associated impacts.

The climatological factors that we utilized for our study included precipitation, snow water equivalent, soil moisture and temperature. We expect tree ring growth to have been negatively impacted overall during these two drought periods due to a lack of moisture. Despite shorter and warmer winters which could have led to extended growing seasons, moisture availability is likely the key limiting growth factor. The primary objective of this project was to analyze the effect of drought on tree ring growth.

Data & Methods

Data

The climatological data we used for our analysis were retrieved from the; PRISM daily dataset, observed daily data from both Carpenter Ridge and Truckee, and hydrologic model simulations. The PRISM Climate Group provides various spatial climatological datasets for the conterminous U.S. (Daly et al., 1994). For this study, we used 1982 – 2014 4x4 km gridded daily precipitation and temperature data (minimum, maximum, and mean temperatures). To identify consistencies or inconsistencies between the PRISM time series and the observed records from the gauges in vicinity of the tree sampling sites we compared the two data sets. Because the records from these in-situ gauges have missing data for the period of interest, the PRISM dataset was selected for precipitation and temperature. We found high correlations between the two datasets but found that the PRISM data slightly overestimated Carpenter Ridge precipitation. To adjust for this we separated the Carpenter Ridge daily precipitation data in
quartiles and adjusted the PRISM data to better match the observed data, ultimately reducing the Carpenter Ridge daily precipitation by 20%.

A soil moisture dataset was simulated for the tree sampling sites by using the Sacramento Soil Moisture Accounting Model (SACSMA) (Burnash, 1995) in conjunction with the Snow 17 Model (Anderson, 1973), using the adjusted PRISM data disaggregated into 6-hour as the model input. For the analysis conducted in this study, we used the simulated 6-hour total soil moisture fraction for the two sites.

Lastly, our daily Snow Water Equivalent (SWE) dataset is based on two snow sensors from the SNOTEL network. These sites are the Truckee (#834) and Independence Camp (#539) to represent the snow conditions in Truckee and Carpenter Ridge, respectively.

**Site Climate**

The study area can be described as having a mild mountain climate, a product of the nearby Pacific Ocean. In this region, most of the precipitation occurs in the winter alternating between rainfall and snowfall, and the summers are generally dry and hot. Snowfall and temperature variability develop an intermittent winter snow pack in high elevations (typically above 1500 m) that melts completely during the spring and early summer. The following are plots (Figures 2-5) of monthly total precipitation, monthly mean temperature, monthly average soil moisture, and monthly average SWE. These plots provide a general idea of the climate in the two sampling sites as well as a glimpse into the primary datasets used.

![Figure 2: Box plots for monthly total precipitation from 1981 to 2014 have been constructed by using daily data and summing these values by month. Carpenter Ridge is in blue and Truckee in red. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points the algorithm considers to not be outliers, and the outliers are plotted individually.](image-url)
From these plots it can be noted that in general Carpenter Ridge receives slightly more rainfall than Truckee, Carpenter Ridge experiences cooler temperatures, has higher soil moisture, and receives more
snow. These factors can be somewhat expected due to the difference in elevation and position of the two sites.

Tree Properties and Chronologies

During the summer of 2014, cores from seven sites and nine tree species of conifers were sampled in a vertical transect along the American River watershed at the Sierra Nevada Mountains. These tree cores were then cross-dated and chronologies of total ring width, early wood width, latewood width and latewood density measured by blue intensity methodology were developed. As mentioned, we have chosen to focus on total ring width at two sites, Carpenter Ridge and Truckee, both with two species each.

Truckee samples include two species of trees, White Fir (*Abies concolor*) and Ponderosa Pine (*Pinus ponderosa*). At Carpenter Ridge we also sampled two species, California Red Fir (*Abies magnifica*) and Mountain Hemlock (*Tsuga mertensiana*). When evaluating limiting growth factors it is important to understand that various species have varying conditions in which they grow the best.
A few notes on our four selected trees species may help our discussion. The White Fir species, located at Truckee, grow best when annual precipitation ranges from 990 mm to 1240 mm [Burns and Honkala, 1990], although they can tolerate annual rainfall as low as 280 mm and as high as 4040 mm. Also at Truckee, Ponderosa pine is typically dominant in warm and dry sites with a short growing season and very low summer precipitation. The Ponderosa pine is found in regions with annual average of 5° to 11° C and can tolerate extreme temperature ranging from -40° to 38° C [Burns and Honkala, 1990]. This species is drought tolerant and summer soil moisture most often determines whether ponderosa pine will grow in a particular area [Burns and Honkala, 1990].

At Carpenter Ridge the California red firs commonly grow in areas that receive between 750 and 1250 mm of precipitation, although they can tolerate annual rainfall as low as 560 mm and as high as 3940 mm. They require climate that in general can be described as ranging from cool and moist to cold and moist [Burns and Honkala, 1990]. As for Mountain hemlock, this species thrives in areas that generally have a cool to cold maritime climate that includes mild to cold winters, a short, warm to cool growing season and moderate to high precipitation [Burns and Honkala, 1990]. Understanding of these tolerances will help to predict limiting growth factors and will ideally be reflected in the growth chronologies.

**Methods: Indices and their derivations**

Using the climatological time series, we have generated various indices to help us determine the relationship between climate and total ring width for the two sites and four tree species. Each index was constructed using water years, which is defined from October 1st to September 30th, and has a value for each year from 1982 to 2014. Following a comprehensive evaluation of various indices, we decided to conduct our study with the following selected indices: peak SWE, peak soil moisture, length of growing season, length of summer, duration of winter, and number of cooling degree-days.

The selected indices are defined and calculated as follows.
Using snow water equivalent two indices were developed, Peak SWE and duration of winter. Peak SWE has unit of mm and was determined by sorting daily SWE values into water years and finding the largest value for each water year. It is important to note that we chose to use a variable peak SWE rather than assigning April 1st SWE as the peak. Peak SWE was allowed to be variable in order to compare the true
peak to the tree ring chronologies. Peak SWE was chosen as an index based on the belief that a higher peak SWE meant more moisture was introduced to the sites for during a given year. The SWE based duration of winter has units of days and has been defined as the number of days between the accumulation of snow (winter onset) and snow melt. Accumulation of snow was deemed as the number of days since October 1st that there were ten days with SWE above 10 mm. Snow melt was defined as the number of days since October 1st that SWE began to decline from its peak. The days elapsed between the timing of the winter onset and the timing of peak SWE is the SWE based duration of winter. Defining duration of winter using SWE was appealing because a longer winter may suggest prolonged SWE and moisture. The figure 7 provides a visual of these indices.

For soil moisture there are three indices; Peak soil moisture [mm³/mm³], the length of the growing season [days], and the length of summer [days]. A visual of the explanations for these indices can be found in figure 7 below.

To find peak soil moisture we began with the soil moisture model which generates soil moisture values on a time scale of six hours. The soil moisture fraction values for each day were averaged and organized into water years. Peak soil moisture was found by determining the largest value during each water year. Peak soil moisture is a representation of the amount of moisture available to the tree for a given year.
Its relationship to total ring width growth is based on the assumption that a higher peak soil moisture, the higher the soil moisture availability for a given water year.

The length of summer was defined as the number of days since the start of the summer drought, when soil moisture falls below 0.15, until the end of the drought, when soil moisture rises back above 0.15. The length of the growing season was specified as the number of days between the warming onset, which is temperature based, and the onset of summer drought, which is soil moisture based. The warming onset was determined by finding the number of days since October 1st that temperature began to rise from its winter lows. To do this we focused on spring months and found when the temperature rose above 5 degrees for five consecutive days. The onset of summer was found by evaluating when the soil moisture fraction dropped below 0.15. The number of days since October 1st that this event occurred was our summer onset index. The number of days between these two indices, the onset of warming and the onset of summer, was the length of our growing season.

Figure 8: This figure plots two water years, 2001 and 2002, in order to better illustrate our Peak soil moisture, the length of the growing season, and the length of summer. This plot uses monthly soil moisture values rather than daily for simplicity, however, our calculations used daily soil moisture data. The peak soil moisture is the maximum soil moisture value for a given water year, as depicted by the yellow dot. The orange dotted line indicates when the soil moisture fraction is 0.15. The beginning of summer is when the soil moisture fraction drops below this line, and the end of summer is when it rises back above 0.15. The number of days between these two points is the length of summer. The warming onset based on temperature has been extrapolated from the following temperature plot. The length of the growing season is the number of days between the two cyan dotted lines, or between the warming onset and beginning of summer.
As for temperature two indices were established, duration of winter and minimum cooling degree-days. The duration of winter as defined by temperature was thought to be associated with the dormancy period of trees. The temperature based duration of winter was defined as the number of days between the cooling onset and warming onset. The cooling onset was the number of days since October 1st with five consecutive days of mean daily average below 5 degrees. The warming onset was defined as the number of days since October 1st in which mean daily temperature began to rise from winter lows followed by five consecutive days of above 5 degrees.

Cooling degree-days is intended to be a measure of how cold the winter was for a given year. Cooling degree-days were calculated by taking the average of a day’s minimum and maximum temperature and cumulatively summing the negative values for each respective water year. The absolute value of the minimum of this cumulative sum was recorded for each water year and served as our cooling degree-day value for that year.

Figure 9: This figure plots two water years, 2001 and 2002, in order to better illustrate our temperature based winter duration. This plot uses monthly mean temperature values rather than daily for simplicity, however, our calculations used daily temperature data. The orange dashed line indicates where it is 5 degrees C. The yellow dots show when there was either a cooling onset, when the temperature dropped below 5 degrees, or a warming onset, when the temperature began to rise above 5 degrees. The number of days between warming and cooling onsets is the temperature based duration of winter. The warming onset is also indicated by a vertical blue dashed line, this timing is what was used to compute the length of the growing season.
Results

Indices

The following figures are stem plots of our various indices for our two sites. Along the x-axis is the year and the y-axis is the units of each respective index. These stem plots are meant to illustrate the various indices and highlight the index values during the two drought periods of interest. They also help to visualize the various indices during drought periods and how they relate to the average index value as indicated by the blue dashed line.

Figure 10: This plot shows the cumulative sum of Cooling degree days for the 2001 water year. The yellow dot indicates the minimum value for this year, the absolute value of this minimum is what was used in our calculations.

Figure 11: The plots show the peak SWE for each year from 1982 to 2014, the left for Carpenter Ridge and the right for Truckee. The dashed line represents the average, the orange dots indicate the first drought period (1986 to 1993), and the yellow dots indicated the second drought period of interest (2010 to 2014).
For the two indices that reflect moisture availability (i.e. peak SWE and peak soil moisture) it was seen that during the two drought periods their values were relatively lower than average. Comparing figures 11 and 12 to the previous stem plots of the tree ring width growth, figure 6, a few inferences were made.

For Truckee, the peak soil moisture plot and both tree ring width growth stem plots were moderately similar in shape especially during our two droughts. In both, peaks can be seen for years 1986, 1988, and 1993 and a drop off seen in 2013 and 2014. Peak SWE for Truckee is also relatively similar to the peak soil moisture and ring width growth plots. All three have drought values below average overall. For Carpenter Ridge the trend was similar. Again, the values for peak SWE, peak soil moisture, and total ring growth were overall below average during the drought years. These observations suggest a high correlation between SWE, soil moisture, and tree ring growth.

Figure 12: The plots show the peak soil moisture for each year from 1982 to 2014, the left for Carpenter Ridge and the right for Truckee. The dashed line represents the average, the orange dots indicate the first drought period (1986 to 1993), and the yellow dots indicated the second drought period of interest (2010 to 2014)
When comparing SWE based winter duration (figure 13) to total ring width growth (figure 6) it is noticeable that Truckee’s SWE based winter duration and Truckee total ring width growth looked similar during our two drought periods, both with peaks around 1990 and 2012. During the most recent
drought, the SWE based winter duration and total ring width growth for the Ponderosa Pine at Truckee were surprisingly similar in their trends. As for Carpenter Ridge, the plots for SWE based winter duration (figure 13) and total ring width growth (figure 6) had moderately similar trends. It seems that during the two drought periods the peaks and lows were in close proximity but perhaps alternated or lagged a year.

The length of the growing season (figure 14) compared to total ring width growth (figure 6) followed a similar scheme as the SWE based winter duration. The length of the growing season seemed to increase from 1986, peak around 1990, and a decrease thereafter, a similar trend occurs in following drought period where there is an increase from 2010, peak around 2011, and a decrease thereafter. The tree ring width growth also seems to have follow a similar trend. Although, this trend was more noticeable for Truckee than Carpenter Ridge.

Temperature based winter duration (figure 15) did not show an exceptionally obvious trend during the two drought periods, although it was slightly similar in shape to the SWE based winter duration plots (figure 13), the length of the growing season (figure 14), and total ring width growth (figure 6).

While studying the length of summer (figure 16) alongside the tree ring width growth plots (figure 6) there are no obvious connections. It seems that the length of summer alternated between above and below average from year to year, the same cannot be said about tree ring width growth.
Lastly, for cooling degree-days (figure 17) it seems that the index values were overall above average during the first drought period and overall below average for the second drought period. Referencing back to the tree ring width growth stem plots (figure 6), it seems that at Carpenter Ridge the California Red Fir experienced above average growth during the first and second drought whereas the mountain hemlock saw below average growth during the first drought and about average during the second. Both the Truckee species, White Fir and Ponderosa Pine, saw below average growth during the first drought and about average during the second. Despite the prospect of Carpenter Ridge being reasonably influenced by cool temperatures it does not seem like either Carpenter Ridge species’ tree ring width growth trends match incredibly well with the cooling degree day plot. The Truckee species also did not show an immediate connection to the cooling degree day index.

**Correlation Coefficients**

Correlation coefficients for our indices are presented in table 1. Those that are highlighted are significantly different than zero with a 99% confidence level. A few other indices were originally included but were removed due to their redundancy, the original table can be found in the appendix part i.

The non-lagged columns contain correlation coefficients for the index versus the tree ring width growth for years 1982 to 2014. The “lagged” columns were generated by plotting the previous year’s index.
against the following year’s growth. For example, to calculate the correlation coefficient for lagged peak SWE we used the peak SWE from 1990 against the tree ring width growth in 1991. For Carpenter Ridge we saw a significant improvement in correlation coefficients post shift. For Truckee it seems like lagging the data was not always as useful.

Table 1: This chart organizes the various correlation coefficients for our indices and tree species growth. CPRA represents the California Red Fir at Carpenter Ridge, CPRT represents the Mountain Hemlock at Carpenter Ridge, TRSA represents the White Fir at Truckee, and TRSP represents the Ponderosa Pine at Truckee. Table captions go above tables.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration Of Winter (days)</td>
<td>0.002</td>
<td>0.129</td>
<td>0.152</td>
<td>0.104</td>
<td>0.237</td>
<td>0.263</td>
<td>0.319</td>
<td>0.384</td>
</tr>
<tr>
<td>Cooling Degree Days (degrees)</td>
<td>-0.047</td>
<td>-0.112</td>
<td>0.368</td>
<td>0.313</td>
<td>-0.108</td>
<td>-0.165</td>
<td>0.095</td>
<td>0.029</td>
</tr>
<tr>
<td>Peak SWE (mm)</td>
<td>0.015</td>
<td>-0.160</td>
<td>0.556</td>
<td>0.732</td>
<td>0.498</td>
<td>0.516</td>
<td>0.493</td>
<td>0.512</td>
</tr>
<tr>
<td>Winter Duration (days)</td>
<td>-0.034</td>
<td>0.086</td>
<td>0.606</td>
<td>0.485</td>
<td>0.491</td>
<td>0.482</td>
<td>0.511</td>
<td>0.550</td>
</tr>
<tr>
<td>Peak Soil Moisture (fraction)</td>
<td>0.079</td>
<td>-0.064</td>
<td>0.458</td>
<td>0.778</td>
<td>0.689</td>
<td>0.567</td>
<td>0.352</td>
<td>0.491</td>
</tr>
<tr>
<td>Growing Season (days)</td>
<td>0.059</td>
<td>-0.148</td>
<td>0.441</td>
<td>0.533</td>
<td>0.131</td>
<td>-0.050</td>
<td>-0.040</td>
<td>-0.029</td>
</tr>
<tr>
<td>Summer Length (days)</td>
<td>0.271</td>
<td>0.235</td>
<td>-0.256</td>
<td>-0.458</td>
<td>-0.271</td>
<td>-0.113</td>
<td>-0.487</td>
<td>-0.598</td>
</tr>
</tbody>
</table>

Moving down the rows it can be seen that there was a correlation between Truckee’s lagged temperature based duration of winter and both the Ponderosa Pine and White Fir. There was also a correlation between Carpenter ridge lagged cooling degree days and the Red Fir and Mountain Hemlock. Perhaps the reason for differences between the sites may be because Truckee is warmer than Carpenter Ridge. Due to Truckee’s increased temperatures perhaps it was the duration of winter that affected
growth rather than the coldness. As a result of Carpenter Ridge’s high elevation, it receives colder temperatures and thus it is the low temperature that was the limiting rather than the duration of low temperatures.

For Snow Water Equivalent both sites showed high correlations for peak SWE. The difference between sites seems to be that Carpenter Ridge showed a stronger signal if the previous year’s SWE was correlated to the following year’s growth and Truckee showed a stronger correlation for non-lagged years. For SWE based winter duration both sites showed relatively high correlations if the index was lagged.

Focusing on soil moisture, both sites showed strong correlations for peak soil moisture, which perhaps may be expected after seeing a strong relationship between growth and peak SWE. Like peak SWE, Carpenter Ridge showed a stronger signal if the previous year’s soil moisture was correlated to the following year’s growth and Truckee showed a stronger correlation when soil moisture was non-lagged. The length of the growing season showed a correlation for both Carpenter Ridge species if the index was lagged but no correlation for Truckee. Lastly, we saw a correlation between the length of summer and Mountain Hemlock and for both Truckee species but only for the lagged index.

Ideally these indices were independent from one another, below are tables of correlation coefficients between each of our seven indices. In general, it seems that our chosen indices were fairly independent from one another, although there were a few unavoidable correlations. The highlighted values indicate correlation coefficients that are significantly different than zero with a 99% confidence interval.

<table>
<thead>
<tr>
<th>Carpenter Ridge</th>
<th>Duration Of Winter (days)</th>
<th>Cooling Degree Days (degrees)</th>
<th>Peak SWE (mm)</th>
<th>Winter Duration (days)</th>
<th>Peak Soil Moisture (fraction)</th>
<th>Growing Season (days)</th>
<th>Summer Length (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp</td>
<td>Duration Of Winter (days)</td>
<td>1.000</td>
<td>0.188</td>
<td>0.225</td>
<td>0.259</td>
<td>0.214</td>
<td><strong>0.463</strong></td>
</tr>
</tbody>
</table>

Table 2: Contains the correlation coefficients between each index at Carpenter Ridge. The highlighted values indicated correlation coefficients with a 99% confidence interval.
<table>
<thead>
<tr>
<th></th>
<th>Cooling Degree Days (Degrees)</th>
<th>SWE Peak SWE (mm)</th>
<th>Winter Duration (days)</th>
<th>Soil Moisture Peak Soil Moisture (fraction)</th>
<th>Growing Season (days)</th>
<th>Summer Length (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Degree Days</td>
<td>0.188</td>
<td>0.225</td>
<td>0.259</td>
<td>0.214</td>
<td>-0.463</td>
<td>-0.112</td>
</tr>
<tr>
<td>Days (Degrees)</td>
<td>1.000</td>
<td>0.392</td>
<td>0.520</td>
<td>0.230</td>
<td>0.262</td>
<td>-0.190</td>
</tr>
<tr>
<td></td>
<td>0.392</td>
<td>1.000</td>
<td>0.520</td>
<td>0.753</td>
<td>0.596</td>
<td>-0.505</td>
</tr>
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<td></td>
<td>0.233</td>
<td>0.520</td>
<td>1.000</td>
<td>0.517</td>
<td>0.409</td>
<td>-0.449</td>
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<td></td>
<td>0.230</td>
<td>0.753</td>
<td>0.517</td>
<td>1.000</td>
<td>0.492</td>
<td>-0.670</td>
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<td>0.262</td>
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<td>1.000</td>
<td>-0.349</td>
</tr>
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<td></td>
<td>-0.190</td>
<td>-0.505</td>
<td>-0.449</td>
<td>-0.670</td>
<td>-0.349</td>
<td>1.000</td>
</tr>
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</table>

Table 3: Contains the correlation coefficients between each index at Truckee. The highlighted values indicated correlation coefficients with a 99% confidence interval.

<table>
<thead>
<tr>
<th>Truckee</th>
<th>Index</th>
<th>Duration Of Winter (days)</th>
<th>Cooling Degree Days (degrees)</th>
<th>Peak SWE (mm)</th>
<th>Winter Duration (days)</th>
<th>Peak Soil Moisture (fraction)</th>
<th>Growing Season (days)</th>
<th>Summer Length (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp</td>
<td>Duration Of Winter (days)</td>
<td>1.000</td>
<td>0.200</td>
<td>0.157</td>
<td>0.429</td>
<td>0.199</td>
<td>0.634</td>
<td>-0.330</td>
</tr>
<tr>
<td></td>
<td>Cooling Degree Days</td>
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<td>1.000</td>
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The indices at Carpenter Ridge (table 2) show more correlation between each other than do the indices at Truckee (table 3). At Carpenter Ridge there was a correlation between the temperature based winter duration and the length of the growing season, which is understandable because they both utilize the warming onset index and thus the end of the winter means the start of the growing season. There was also a relationship between Peak SWE and four other indices; SWE based duration of winter, peak soil moisture, the length of the growing season, and the length of summer. This was also reasonable because more SWE may require a longer winter to accumulate, more snow may mean more melt that can replenish soil moisture to increased levels, more snow also suggests prolonged melting and prolonged soil moisture which may extend the growing season, and thus shorten the length of summer. Using this logic it is also understandable that the SWE based duration of winter had relatively high correlations with peak soil moisture and the length of the summer and that peak soil moisture had high correlations with the length of the growing season and the length of the summer.

The only strong correlations at Truckee (table 3) were between the temperature-based duration of winter and the length of the growing season, peak SWE and peak soil moisture, and peak soil moisture and the length of the summer. These correlations can be justified using previous logic. The growing season and temperature based duration of winter both utilized the warming onset index, peak SWE adds additional moisture to an environment which may lead to increased soil moisture, and increased soil moisture may mean for prolonged soil moisture and a shorter summer. Perhaps there is a difference between index correlations between the two sites due to the differences in location and climate of the two sites. Truckee receives less snow and increased temperatures which may influence moisture due to increased evaporation and evapotranspiration.

**Scatter Plots**
Related to the correlation coefficients from table 1 are scatter plots for each of our indices, lagged and non-lagged for years 1982 to 2014. Below are only a few of the scatter plots generated, Carpenter Ridge’s peak soil moisture (figure 18) and SWE based winter duration (figure 19) and Truckee’s peak soil moisture (figure 20) and SWE based winter duration (figure 21). Scatter plots for the other indices are presented in the appendix part ii. Despite significant correlations between a handle full of indices and total ring width growth, there are a few exceptions to the trend which can be seen in the plots below. In particular, there were a handle full of years that reside within the drought periods that were exceptions to the trend.

Focusing on the plots with significant correlation coefficients we looked at the lagged plots for both Carpenter Ridge indices, the non-lagged plot for Truckee’s peak soil moisture, and the lagged plot for Truckee’s SWE based winter duration.

Figure 18: Scatter plots for peak soil moisture vs total ring width growth for years 1982 to 2014 are presented above. The left is for the non-lagged index and the right for the lagged index. The Red fir (CPRA) are blue dots and the Mountain Hemlock (CPRT) are red dots. The filled dots are drought years and have their respective year next to their dot.
Figure 19: Scatter plots for SWE based winter duration vs total ring width growth for years 1982 to 2014 are presented above. The left is for the non-lagged index and the right for the lagged index. The Red fir (CPRA) are blue dots and the Mountain Hemlock (CPRT) are red dots. The filled dots are drought years and have their respective year next to their dot.

Figure 20: Scatter plots for peak soil moisture vs total ring width growth for years 1982 to 2014 are presented above. The left is for the non-lagged index and the right for the lagged index. The White Fir (TRSA) are blue dots and the Ponderosa Pine (TRSP) are red dots. The filled dots are drought years and have their respective year next to their dot.
In the various scatter plots it is noticeable that a few years frequently seem avoid the overall plot trend. These years would be 1988, 1989, 1991, 1992, and 1993. The four plots presented above show the deviation the most, however, these years can be seen out of line in other index scatter plots as well. In general the plots above show that during these years even though peak soil moisture and the SWE based duration of winter were moderately high, the total ring width growth was proportionately lower than the trend would suggest. When creating scatter plots it may be expected to have a number of outliers that do not fit the trend, however it is curious that the outliers were repeatedly a handful of specific drought period years.

Conclusion

Carpenter Ridge and Truckee experience moderate climates and neither site is located at the ecological limits of the tree species, this makes identifying limiting factors more difficult. As stated previously for Carpenter Ridge we thought this factor may have been temperature due to its relatively high elevation which could lead to colder winter temperatures that in turn affect growth. For Truckee we thought this
factor may have been moisture due to decreased snow and precipitation. After preforming our analysis it was apparent that soil moisture and SWE have a strong role in growth and that temperature did not necessarily play a vital part.

The correlations between snow and soil moisture seem to be the strongest. However, many noteworthy correlations only arose if the index was lagged a year. Carpenter Ridge in particular only showed strong correlations if the index was lagged. The reasoning behind this is unclear. Although, it could perhaps be attributed to deeper root zones than initially estimated. We could speculate that the trees are tapping into soil moisture from previous years that has been persevered in deeper soils. However, we would need to conduct further research to establish any certainties or make any further assumptions.

In regards to our two selected drought periods, we initially predicted that we would see a change in limiting factors during times of drought. We thought that perhaps during drought moisture or temperature may become especially limiting due to the exceptional conditions associated with drought. However, we found that in general the drought years seemed to follow the same trend as non-drought years, with a few exceptions as mentioned previously. The reasoning for these exceptions is unknown, further analysis could be helpful to better understand these particular years. In these years it may be beneficial to focus on other indices or a combination of indices to determine a limiting factor(s).

Moving forward, it would be advantageous to return to our sites for further inspection. In order to address the link between lagged moisture availability and tree ring growth we should evaluate soil moisture and the root zone on a deeper scale. This may help determine whether or not moisture from the previous year was stored for the following year and if the root zone had access to this moisture. With respect to the irregular drought years (1987-1989 and 1991-1993) it may be useful to analyze these years separately. Focusing on these specific years and utilizing our full set of indices may provide insight on the limiting factors for these years.
References


Crowley, T. J. and Lowery, T. S. 2000. How warm was the medieval warm period? Ambio 29, 51-54.


Schweingruber, F. H., Bartholin, T., Schaer, E., Briffa, K.R. 1988b. Radiodensitometric-dendroclimatological conifer chronologies from Lapland (Scandinavia) and the Alps (Switzerland). *Boreas* 17, 559-566.


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http://www.jstor.org/stable/41711683
Appendices

**Appendix i: Correlation Coefficients: A Complete Table**

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Appendix ii: Index Scatter Plots

Carpenter Ridge

Temperature:

[Scatter plots showing duration of winter (temp) vs CPRA/CPRT 1982 to 2014 and shifted versions with correlation coefficients.]
Soil moisture:

Carpenter Ridge Peak Soil Moisture vs CPRA/CPRT 1982 to 2014

Carpenter Ridge Peak Soil Moisture vs CPRA/CPRT 1982 to 2014, shifted

Carpenter Ridge Length of Growing Season vs CPRA/CPRT 1982 to 2014

Carpenter Ridge Length of Growing Season vs CPRA1/CPRT1 1982 to 2014, shifted
Truckee

Temperature:
Soil Moisture: