TREE-RING RESEARCH, *Vol. 67(1), 2011, pp. 51–55*

RESEARCH REPORT

INCORPORATING CLIMATOLOGICAL TECHNIQUES TO IMPROVE TREE-RING SITE SELECTION IN COMPLEX TERRAIN

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ABSTRACT

Dendroclimatologists often approach field work with the intent of reconstructing a particular climate variable (*e.g.* temperature, streamflow, precipitation). Although guidelines exist for species and site selection, isolating the signal of interest is difficult in areas with complex terrain or a lack of ideal sites. In this case study, I suggest climatological techniques for a more efficient sampling scheme and apply these techniques to identify criteria for selecting sites sensitive to winter precipitation in the north-central Rocky Mountains. These techniques include examining factors influencing the regional response of tree growth to climate by utilizing the International Tree-Ring Databank (ITRDB), using eigenvector analyses to identify modes of variability between sites, and delineating climate regions based on the variable of interest through climate regionalization. Results suggest that low- or mid-elevation *Pseudotsuga menziesii* sites should be targeted for maximizing the winter precipitation signal in the case study area. The season of precipitation impacting growth was found to be a major component of the overall variability between sites.

Keywords: Dendroclimatology, regionalization, site selection, Rocky Mountains, climate, western United States, winter precipitation, ITRDB.

INTRODUCTION

Researchers often seek to reconstruct a particular climate variable for their studies, but signal strength for that variable cannot be entirely determined until the time-consuming process of sample collection and processing is complete. In this research, I seek to capture a winter precipitation signal in the north-central Rocky Mountains. Fritts (1976) provides guidelines for site selection that employ basic principles of dendrochronology, particularly the law of limiting factors and the concept of ecological amplitude. For a precipitation signal, these guidelines would suggest sampling species growing near their arid forest limits on particularly moisture-limited and well-drained sites, while at the same time avoiding species growing near their upper elevational limits that may have a temperature-influenced signal.

The north-central Rocky Mountains are relatively moist, topographically complex, and contain areas of overall high elevation. It can be quite difficult to locate moisture-sensitive tree-ring sites, particularly those with trees over 300 years old, and sites in close proximity to each other sometimes differ in the climate variable their growth most strongly reflects. The traditional site-selection guidelines are not always effective for obtaining a precipitation signal in this area, and isolating a winter precipitation signal can be even more difficult. The objective of this study is to suggest climatological techniques that others may find useful for improving tree-ring site selection and to present a case study utilizing these methods in a region of complex terrain. This is done through two forms of eigenvector analyses and a comparison of climate data with tree-ring site characteristics hypothesized to influence precipitation signal strength, including location, elevation, and species.

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DATA AND METHODS

The 48 contiguous United States are divided into a total of 344 climate divisions. Each state is subdivided into 10 or fewer divisions, and the climate divisions are numbered sequentially within each state (Guttman and Quayle 1996). Monthly divisional climate data integrate observations from representative stations within the division to produce a regional climate average (Guttman and Quayle 1996).

All available chronologies of likely moisture-sensitive species located within approximately 300 km of one of the three climate divisions of interest (Wyoming divisions 1, 2, and 4; Figure 1) were downloaded from the International Tree-Ring Databank (ITRDB) (http://www.ncdc.noaa.gov/paleo/treering.html). Raw ring-width measurements from the ITRDB were standardized in ARSTAN (Cook 1985) using a negative exponential curve or straight line to remove the growth trend. The resulting dataset included 14 *Pinus flexilis* (limber pine) chronologies, four *Pinus ponderosa* (ponderosa pine) chronologies, and 19 *Pseudotsuga menziesii* (Douglas-fir) chronologies. I obtained monthly climate division precipitation data from the National Climatic Data Center (http://www.ncdc.noaa.gov) and tested the tree-ring chronologies for monthly and seasonal correlations with precipitation in each of the climate divisions of interest. These results were examined by species, elevation, and location in order to identify patterns of variation.

Gridded (4 km) precipitation data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) data set (http://www.prism.oregonstate.edu) were acquired for 1895–2006. Monthly precipitation averages and standardized anomalies for 1895–2005 were calculated for each grid point using these PRISM data. The resulting grid was resampled to 16 km to facilitate further analyses.

Principal components analysis (PCA), an eigenvector-based technique that is common in climatological studies, was then employed in two separate ways to examine the data. PCA was first applied to the ITRDB tree-ring chronologies as a data reduction technique, removing redundancy from the set of correlated variables by clustering together variables that represent an underlying factor and are relatively independent of the variables forming other factors (Kachigan 1982). A varimax rotation, which maximizes the sum of the variances of the squared loadings and forces factors to be orthogonal, was used to redefine the factors and make sharper distinctions between their differences (Kachigan 1982). I retained four PCs based on a scree test (Cattell 1966) and the retention of eigenvalues >1.0. The resulting principal components (PCs) were tested against climatic indices of seasonal precipitation and snow water equivalent data to better understand mechanisms controlling their shared variance.

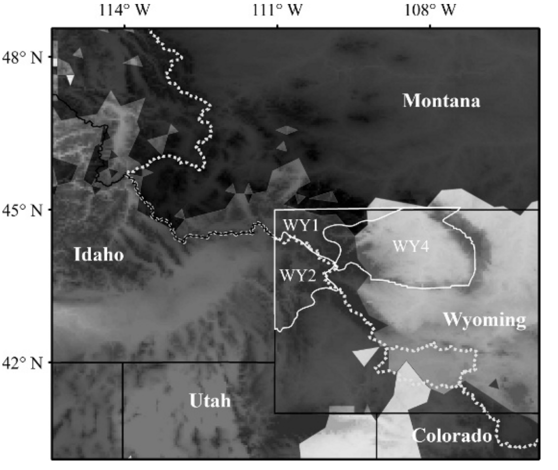

Figure 1. Climate regions based on climate regionalization of cool-season (Nov–Apr) precipitation anomalies. The four shades of gray denote the spatial boundaries of maximum loading on the four eigenvectors. The three Wyoming climate divisions of interest are outlined in white, and the continental divide is shown for reference with a dotted line.

A climate regionalization was then conducted using PCA. The climate regionalization technique has been widely used in synoptic climatology studies to spatially divide continuous climate data into homogenous regions based on a specific parameter of interest (*e.g.* Yarnal 1993; Comrie and Glenn 1998; Miller and Goodrich 2007; Abatzoglou *et al.* 2009). In this case study, I used cool-season (Nov–Apr) precipitation anomalies to group regions that experience simultaneous wet and dry years. Regions were delineated using a maximum-loading approach following a varimax rotated PCA. Rotation is necessary in a climate

Table 1. Tree-ring chronologies (grouped by distance from the chronology site location to the centroid of the climate division, species, and elevation) were correlated with cool-season (Nov–Apr) precipitation (ppt). Correlations significant at the 0.05 level were averaged together for each class and are summarized below.

a)	**Distance**	**WY1 ppt**	**WY2 ppt**	**WY4 ppt**
	0–99 km	0.21	0.08	0.26
	100–349 km	0.29	0.25	0.30
	350–599 km	N/A[1]	0.24	0.22
b)	***Species* (n)**	**WY1 ppt**	**WY2 ppt**	**WY4 ppt**
	Pseudotsuga menziesii (19)	0.32	0.26	0.26
	Pinus flexilis (14)	0.09	−0.01	0.27
	Pinus ponderosa (4)	N/A	N/A	N/A
c)	**Elevation (n)**	**WY1 ppt**	**WY2 ppt**	**WY4 ppt**
	1,000–1,599 m (5)	0.35	0.25	0.28
	1,600–2,199 m (16)	0.31	0.28	0.26
	2,200–2,799 m (16)	−0.02	0.07	0.25

[1] N/A denotes that no chronologies in that category were significantly correlated with winter precipitation in the climate division.

regionalization to identify spatial patterns of variation (Yarnal 1993), and rotated PCs produce more stable and physically realistic patterns (Abatzoglou *et al.* 2009). In the maximum-loading approach, each grid cell is assigned to the eigenvector upon which it loaded most highly. One limitation of the regionalization method is that the researcher must make *a priori* judgments concerning how many regions (eigenvectors) to retain (DeGaetano 2001). I chose to retain four regions for this case study after testing several iterations of the regionalization and utilizing the scree test.

RESULTS

Regional Chronologies and Winter Precipitation

The ITRDB chronologies located in the study region were used to examine potential factors underlying the varying ability of sites in this region to reflect winter precipitation. Sites located within (or in close proximity to) the climate division of interest were expected to better reflect the divisional climate record than those farther away. However, no clear spatial pattern was discernable from a visual inspection of the correlation between individual chronologies and divisional climate data, and analyses based on Euclidean distance to the climate division of interest confirmed that the sites lack a straightforward spatial relationship (Table 1). This is likely because of the region's complex topography, as climate conditions change over short distances.

The three tree species examined in this study are all considered to be moisture-sensitive under appropriate site conditions (Fritts 1976). In the analyzed ITRDB sites, *Pseudotsuga menziesii* chronologies were more highly correlated with winter precipitation than *Pinus flexilis* or *Pinus ponderosa* chronologies (Table 1). However, elevation appears to be the key factor determining winter precipitation strength. Lower-elevation sites are more strongly correlated with climate division winter precipitation data than high-elevation sites (Table 1). Elevations of the analyzed sites ranged from 1,100–2,700 m. Although each analyzed elevation band contains a mixture of species, *Pseudotsuga menziesii* sites dominate the lower elevations and *Pinus flexilis* sites are more prevalent at higher elevations. Very few of the individual high-elevation sites were significantly correlated with winter precipitation, and those correlations that were significant covered a wide range of values ($r = -0.26$ to $+0.25$; $p < 0.05$).

ITRDB Principal Components Analysis

The PCA of tree-ring sites yielded four PCs with a clear geographic pattern (Figure 2). When compared to the climate indices, these PCs were found to be distinguished by the season of precipitation recorded by their corresponding tree-ring chronologies, which was in turn related to elevation of the site locations. Chronologies that loaded most highly on PC1 were low-elevation sites

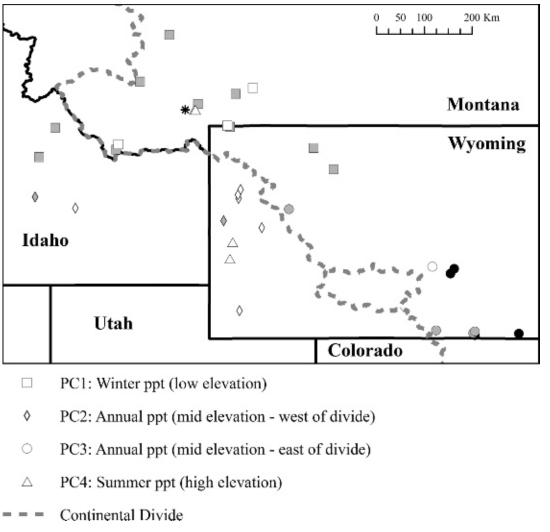

Figure 2. Locations of the 37 ITRDB chronologies, their PC membership (see legend), and species: *Pseudotsuga menziesii* sites (gray), *Pinus flexilis* (white), and *Pinus ponderosa* (black). Continental divide shown by dashed gray line; asterisk marks location of four overlapping sites on PC4 (two *Pinus flexilis* and two *Pseudotsuga menziesii* sites).

consisting primarily of *Pseudotsuga menziesii* that had a strong relationship to winter precipitation. PC2 and PC3 chronologies best reflected annual precipitation, but were differentiated by their location west (PC2) or east (PC3) of the continental divide and by dominant species: PC2 membership was 75% *Pinus flexilis*, whereas PC3 contained a mix of all three species (Figure 2 and Table 2). PC4 chronologies, which were 67% *Pinus flexilis*, were characterized by higher elevations and stronger correlations to summer precipitation.

Climate Regionalization

One possible sampling approach would be to situate potential sites within the specific climate divisions of interest (in this case, WY1, WY2, and WY4). However, the results presented here have shown that the region encompassing these climate divisions lacks a straightforward relationship between proximity to the climate division and winter precipitation signal strength. The climate regionalization conducted for this study provides a possible explanation: climate regions based on winter precipitation anomalies follow different boundaries than the divisional boundaries (Figure 1). Although climate divisions stop at state lines and conform to the continental divide, this regionalization shows that these borders do not delineate homogenous climate regions. In particular, there is a climatic "spillover" across the Rocky Mountains. Climate divisions WY1 and WY2, along with the western portion of WY4, all represent part of the same climate region as delineated by cool-season precipitation. Designing a sampling strategy that distributes sites across climate regions defined by the variable of interest, rather than by divisional boundaries, should help avoid redundant sampling and optimize efforts in the field and laboratory.

Table 2. PC membership by species.

Species	PC1	PC2	PC3	PC4
Pseudotsuga menziesii	79%	25%	44%	33%
Pinus flexilis	21%	75%	11%	67%
Pinus ponderosa	0%	0%	44%	0%

DISCUSSION AND CONCLUSIONS

Elevation appears to be the major factor influencing the ability of trees to capture a winter precipitation signal in the north-central Rocky Mountains, with lower-elevation sites recording a stronger signal. The lower-elevation sites may have a stronger climate signal because of their higher overall growth variability, *i.e.* trees growing at these sites are more limited by environmental factors and are therefore more sensitive climate recorders (Fritts 1976). These sites also tend to experience higher summer drought stress and may be particularly dependent on soil moisture recharge from winter precipitation that fuels early spring growth. Higher-elevation sites can be negatively impacted by heavy winter precipitation if the benefits of soil moisture recharge are outweighed by delayed onset of spring or slowed initial growth (Fritts 1976; Vaganov *et al.* 1999). Of the tree species analyzed, *Pseudotsuga menziesii*, which dominates the low-elevation sites, was best able to capture the winter precipitation signal.

The season of precipitation impacting growth is a major component of the overall variability between sites in the study region (see Figure 2).

Chronologies sharing similar modes of variation were grouped together through PCA, allowing for identification of underlying factors controlling that variance. The four retained PCs were found to be distinguished by precipitation seasonality and site elevation.

In this study, proximity of tree-ring sites to the climate division of interest did not necessarily lead to increased correlation with winter precipitation. Blasing *et al.* (1981) suggested that tree-ring growth may have more shared variance with regionally averaged climate division records than with nearby single station data, and divisional data have been widely adopted by dendrochronologists for site selection, response function analyses, *etc.* However, climate divisions in the western United States that cover broad geographical areas with complex topography do not necessarily represent homogenous climatic units. Decisions on where to place divisional boundaries have often been influenced by factors other than climate, such as political delineations or user needs (*e.g.* crop districts or drainage basins) (Guttman and Quayle 1996). As shown in this study's climate regionalization, sites in different climate divisions can be part of the same climate region and reflect a similar climate signal. Conversely, sites within the same climate division may behave differently in a climatic sense, particularly in spatially broad divisions with large elevation changes (*e.g.* WY4 [Figure 1]). The use of climatological techniques such as regionalization to determine climate regions may therefore improve site selection.

Incorporating climatological information and techniques prior to site selection and field sampling should lead to data that better capture the climatic signal of interest. The results of this case study suggest that low- and mid-elevation *Pseudotsuga menziesii* sites should be targeted for maximizing the winter precipitation signal in the north-central Rocky Mountains. Preliminary results from recent field sampling in the region indicate that this is a promising approach for improving the site-selection process. A more detailed study incorporating these new sites, which will be used for a reconstruction of snow-charged streamflow, is in preparation.

ACKNOWLEDGMENTS

This project was supported by the Society for Women Geographers through a Pruitt National Fellowship and by the United States Environmental Protection Agency (EPA) under the Science to Achieve Results (STAR) Graduate Fellowship Program. EPA has not officially endorsed this publication and the views expressed herein may not reflect the views of the EPA.

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Received 10 October 2008; accepted 14 April 2010.