A 545-YEAR DROUGHT RECONSTRUCTION FOR CENTRAL OREGON

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Abstract: Using a 545-year ponderosa pine (*Pinus ponderosa*) tree-ring chronology, we examine the drought history of central Oregon to: (1) determine the relationship among drought, ENSO (El Ni o/Southern Oscillation), and the PDO (Pacific Decadal Oscillation), and (2) compare the climatic sensitivity of ponderosa pine and western juniper (*Juniperus occidentalis*) to determine their suitability as interchangeable climate proxies. Our climatic reconstruction explained 35% of the variance in historical Palmer's Drought Severity Index (PDSI) values and revealed severe drought periods during the 1480s, 1630s, 1700s, and 1930s. The most sustained drought period in our reconstruction occurred during the 1930s, with the most severe single drought year occurring in 1489. We found a significant ($p \leq .01$) but weak relationship between our ponderosa pine chronology and ENSO and the PDO, explaining 9% and 12% of the variation respectively. Both ponderosa pine and western juniper record periods of severe regional drought, but western juniper is more sensitive to regional and seasonal climatic variations, whereas ponderosa pine is more responsive to temperature change. These differences suggest that their substitutability as climate proxies in dendroecological studies is limited. [Key words: dendroclimatology, El Ni o/Southern Oscillation, Pacific Decadal Oscillation, drought, Pacific Northwest.]

INTRODUCTION

Recent scenarios of global warming suggest that future changes in global and regional climate may become both more intense and more frequent (Fedorov and Philander, 2000; Urban et al., 2000; Cole, 2001). Such variability is significant in the Pacific Northwest, where climatic cycles have a strong influence on the regional and local economies (Mantua et al., 1997; Mote et al., 1999) and environmental processes (Redmond and Koch, 1991; Bitz and Battisti, 1999; Mote et al., 1999; Dale et al., 2001). Nonetheless, the direct relationship between climate and long-term environmental processes is poorly understood, in part because historical records are not sufficient to reveal the range of climatic variability and its effects (e.g., Dale et al., 2001).

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Temporal variations in historical climatic records show an oscillating pattern between warm-dry and cool-wet periods over much of the Pacific Northwest (Mote et al., 1999), and can be related to broader-scale patterns of climatic variability, such as the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). During El Niño years, the Pacific Northwest typically experiences drier and warmer than average winters and drought conditions during the growing season; during La Niña years the Pacific Northwest typically experiences cool, wet conditions and flooding (e.g., Redmond and Koch, 1991; Taylor and Hannan, 1999; McCabe and Dettinger, 1999; Mote et al., 1999). The Pacific Northwest's teleconnections with ENSO are mediated by climatic variation in the Aleutian Low. During El Niño events, the Aleutian Low is strengthened and deepened, splitting the storm track so that storms bypass the Pacific Northwest; hence, El Niño winters are warmer and drier than average in the region. La Niña events weaken the Aleutian Low, thereby directing cool, wet Pacific storms toward the Pacific Northwest (Mote et al., 1999).

The Pacific Decadal Oscillation is a longer-term (15- to 35-year) fluctuation in pressure gradients over the northern Pacific (poleward of 20°N) that is more directly connected to climate in the Pacific Northwest than ENSO (Mantua et al., 1997). During warm (positive) PDO events, the Aleutian Low is strengthened over the Pacific Ocean and the jet stream is diverted northward and southward, forcing storms to bypass the Pacific Northwest. During cool (negative) PDO events, the Aleutian Low is weakened and the jet stream directs storms toward the Pacific Northwest. The PDO was in cool phases from 1900–1925 and 1945–1975 and was in warm phases from 1925–1945 and 1975 to about 1995. The PDO appears to have reversed phases in the mid-1990s, though data are inconclusive (Mote et al., 1999). Little is known about the PDO prior to the start of historical records around 1900 (Linsley et al., 2000; Urban et al., 2000; Biondi et al., 2001; Gedalof and Smith, 2001).

The PDO is related spatially and temporally to ENSO, and tropical forcing may dominate north Pacific variability (Mantua et al., 1997; Bitz and Battisti, 1999; Linsley et al., 2000). When PDO and ENSO are simultaneously in warm phases they have a reinforcing effect causing a deepening of the Aleutian Low and winters in the Pacific Northwest to be exceptionally warm and dry. When ENSO and PDO are in cool phases together, winters in the Pacific Northwest are exceptionally cool and wet (Mote et al., 1999). Both ENSO and the PDO appear to be increasing in intensity and reversing phases more frequently with the 20th century climatic-warming trend (Trenberth and Hoar, 1997; Stahle et al., 1998; Urban et al., 2000; Cole, 2001).

In a warming global climate where hemispheric climatic variability is likely to intensify, understanding the relationship between regional and hemispheric climate enhances the development of long-term forest management strategies (Dale et al., 2001). ENSO events have been shown to be important in controlling fire, insect outbreak, and episodic tree mortality in several regions, including the southwestern United States (e.g., Swetnam and Betancourt, 1990, 1998), southern Rocky Mountains (Woodhouse, 1993; Veblen et al., 2000), southern South America (e.g., Kitzberger et al., 2001), and elsewhere in the Pacific Northwest (Heyerdahl, 1997).

Little research, however, has directly examined the role of ENSO and the PDO in the interior Pacific Northwest. This has created a gap in our understanding of how the climate of central Oregon is related to hemispheric climatic variability and how large-scale climatic patterns influence regional-to-local-scale forest processes and disturbance regimes.

Tree-rings provide a useful proxy for extending long-term regional climatic records and provide evidence of past regional climate, its relationship to large-scale climatic patterns, and the range of climatic variability (e.g., Fritts, 1976; Hughes et al., 1982; Lough and Fritts, 1985). Several tree-ring studies have reconstructed regional climate for central Oregon (Keen, 1937; Graumlich, 1987; Garfin and Hughes, 1996; Knapp et al., 2001, 2002), demonstrating that climatic variability for the Pacific Northwest is highly variable over time (Graumlich, 1987; Mote et al., 1999) and space (Knapp et al., 2002).

Long-term reconstructions of forest disturbance also often rely on tree-ring chronologies and frequently incorporate two different tree species: one for the climatic reconstruction (a climate proxy) and the other for the disturbance reconstruction (e.g., Swetnam et al., 1985; Heyerdahl, 1997; Dale et al., 2001; Speer et al., 2001). Different tree species, however, may not share a similar response to climate, and little work has compared the specific responses of different species to climatic variation. These questions concerning the long-term climate of central Oregon and the suitability of different tree species as climate proxies in disturbance reconstructions provide the context of this study. Specifically we seek to develop a long-term drought record for central Oregon and compare the timing of drought to ENSO and PDO, and second, to compare tree-ring chronologies for ponderosa pine (*Pinus ponderosa* var. *ponderosa*) and western juniper (*Juniperus occidentalis* var. *occidentalis*) to determine if these species respond similarly to climatic variation.

STUDY AREA

Our study area is in Lava Cast Forest (LCF), located in the northern portion of Newberry National Volcanic Monument in central Oregon (43.69°N, 121.25°W, 1500 m; Fig. 1). LCF includes a collection of small, forested cinder cones (kipuka) isolated from the contiguous forest by shallow, 5,800- to 6,200-year-old lava flows (Peterson and Groh, 1969).

The climate of central Oregon is semi-arid, controlled by a rainshadow effect from the Cascade Mountains to the west and characterized by a growing season of less than 60 days (Taylor and Hannan, 1999). Average annual precipitation at the nearest meteorological station in Bend, Oregon (44.06°N, 121.28°W) is 297 mm. This value is at least 60 mm less than the mean annual precipitation at LCF based on the minimum moisture requirements for ponderosa pine in the Pacific Northwest (Franklin and Dyrness, 1988). Precipitation during summer convective storms nearly equals the winter snowfall regime. Average temperatures in Bend, Oregon range from 0°C in January to 17.3°C in July (Oregon Climate Service, 2001).

Vegetation at the study site is dominated by ponderosa pine, lodgepole pine (*Pinus contorta*), and a grand fir-white fir hybrid (*Abies grandis-A. concolor*). The distribution of ponderosa pine communities is strongly linked to available soil

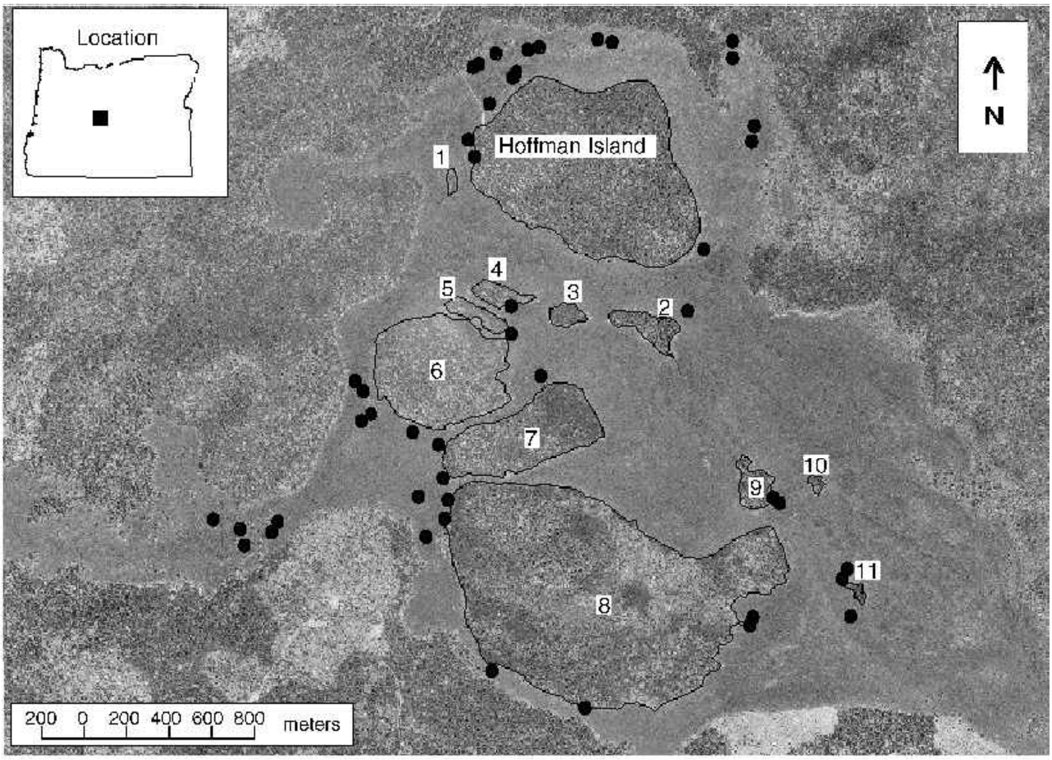

Fig. 1. Location of Lava Cast Forest (LCF) and sampled trees. Black circles represent trees sampled in the climate reconstruction. Numbers identify forest isolates (kipuka).

moisture, as controlled by the loose-textured, pumice soils that allow deep root penetration and have a high moisture-holding capacity (Franklin and Dyrness, 1988). Interspersed within the lava flows at LCF (Fig. 1) are isolated ponderosa pines that exceed 500 years in age. Although the roots of these trees may penetrate through the lava to finer substrates, these trees are severely moisture-limited because of transpirative stress caused by high summer surface temperatures and desiccation from unobstructed winds.

METHOD

Drought Reconstruction

Our drought reconstruction is based on paired increment cores taken at breast height (1.4 m) from each of 50 isolated ponderosa pine trees growing on lava flows at LCF. We reduced the number of ecological variables affecting tree growth by sampling trees lacking close neighbors, evidence of fire or lightning scarring, visible presence of mistletoe infection, and wind damage (Fritts, 1976). Cores were dried, glued to prefabricated wooden core mounts, and sanded with progressively finer grit sandpaper (Stokes and Smiley, 1968). All cores were cross-dated using the list method (Yamaguchi, 1991) by identifying marker years in the wood (i.e., narrow rings, notable latewood width, and wide rings) based on previous ponderosa pine chronologies developed in the study area. Once calendar years were assigned to each ring, ring-width series were developed by measuring each core to the nearest 0.01 mm using a Velmex measuring bench.

Visual crossdating was statistically verified using the program COFECHA (Holmes, 1999). We developed our master chronology from cores having high interseries correlations (>.40) and high mean sensitivities (>.20). The program ARSTAN (Cook and Holmes, 1999) was used to detrend and standardize the series into index values and to remove low frequency, long-term biological growth trends that detract from the higher frequency climatic signal. Series were first detrended with a curve of best fit (negative exponential or linear regression line) and second, with a cubic smoothing spline. The cubic smoothing spline acted as a curved running average of the series and removed additional nonclimatically induced variance from the series (Cook and Peters, 1981). The index values of each series were then averaged to develop the site chronology.

The site chronology was calibrated with instrumental climatic data from 1930–1999 with the remaining available data (1900–1929) used for independent verification (Cook, 1992). We used four climatic variables from uninterrupted instrumental records showing the strongest relationships with tree growth: precipitation at Bend, Oregon, precipitation for Oregon Climate Division 7, temperature for Oregon Climate Division 7, and Palmer's Drought Severity Index (PDSI) for Oregon Division 7 (NCDC, 2001). The PDSI measures the departure of moisture supply from average conditions over several months based on temperature, precipitation, soil moisture, and the duration of drought (Palmer, 1965), each of which directly influences ponderosa pine growth at LCF. The PDSI includes data from the month of interest and several preceding months. Similarly, tree growth is controlled by the aggregated effects of several months' climate, thus PDSI and tree growth are often strongly linked (Fye and Cleaveland, 2001).

We examined seasonal relationships between tree growth and each of the four climatic variables by comparing Pearson's correlation coefficients during a 20-month period (the year of tree growth and the preceding 8 months). The months with significant relationships to tree growth were then averaged and regressed with the site chronology. We used the strongest seasonal relationship for each of the four climatic variables to calibrate the regression model. Using the resulting regression equation we reconstructed historical values for each variable based on our site chronology. We tested for lags in the relationship between the site chronology and aggregated months of climatic data using lagged cross-correlation functions.

We assessed the calibrated model by comparing it to data withheld for verification (1900–1929) using Pearson's correlation coefficient and the reduction of error statistic (RE) (Fritts, 1976; Gordon, 1982; Cook, 1992). Residuals were analyzed using bivariate scatterplots, histograms, and the Durbin-Watson statistic to confirm that the assumptions of linear regression models were satisfied. Once the model was verified, we used its regression equation to reconstruct climate for the entire length of the chronology.

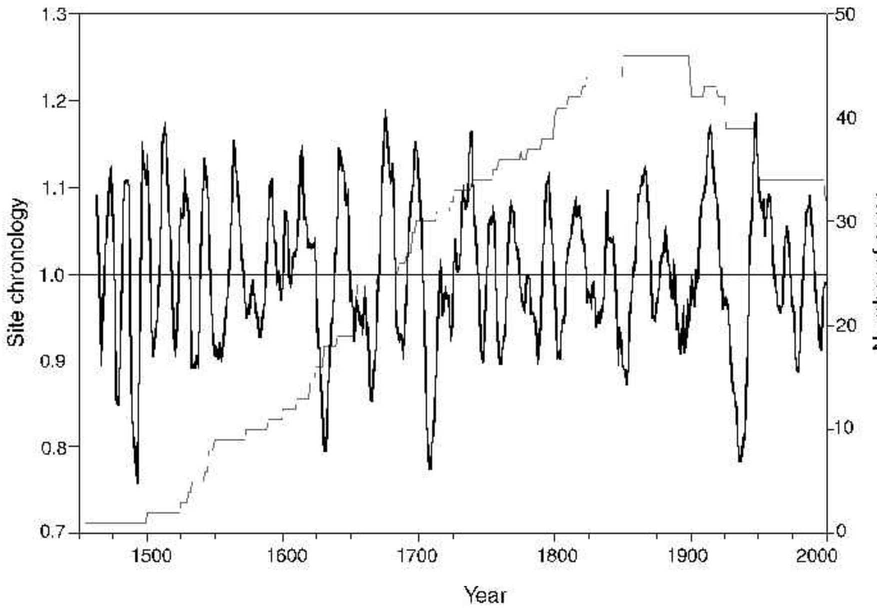

Fig. 2. Site chronology and sample depth. Black line is 8-year moving average of the site chronology. Grey line is the number of cores included in each year of the reconstruction. The left y-axis represents tree-ring index values from the site chronology; values greater than 1 indicate above average tree growth, values less than 1 indicate below average tree growth.

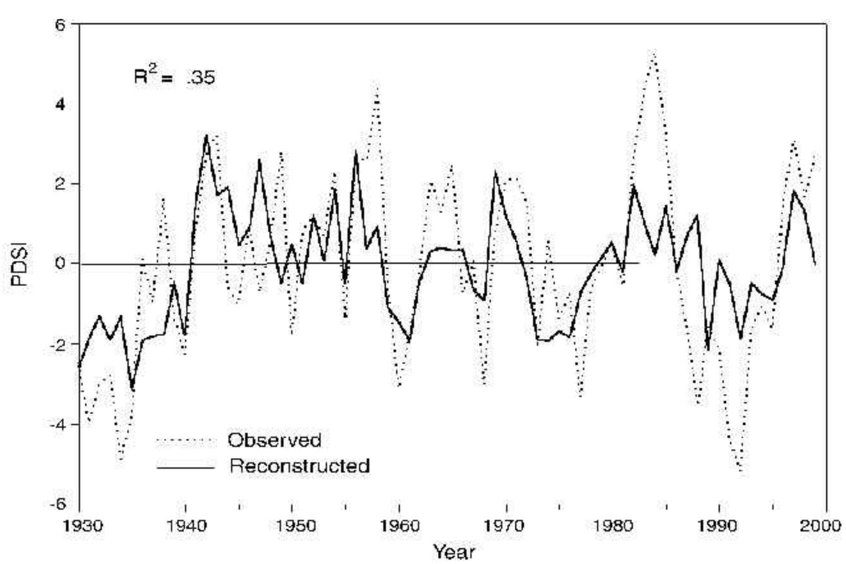

Fig. 3. Observed and reconstructed Palmer's Drought Severity Index (PDSI) for calibration period, 1930–1999. Reconstructed PDSI explains 35% of the variance in observed PDSI. The PDSI is a standardized index between approximately -6 (extreme drought conditions) and +6 (extreme wet spell). Y-axis represents values of PDSI where any value greater than 0 indicates above average precipitation and any value less than 0 represents below average precipitation.

Table 1. Correlations of Climate Variables and Site Chronology for 18 Months Surrounding Year of Tree Growth from 1900 to 1999[a]

Time period		Climate variable			
Year	Month	Div. 7 PDSI[b]	Bend ppt.[c]	Div. 7 ppt.[d]	Div. 7 temp.[e]
Year -1[f]	May	0.350			
	June	0.344			
	July	0.377			
	August	0.358	0.231		
	September	0.383			
	October	0.499			
	November	0.490			
	December	0.500		0.214	
Year 0[g]	January	0.538	0.239	0.297	
	February	0.506			
	March	0.420			
	April	0.331			
	May	0.383	0.210	0.257	
	June	0.470	0.255	0.379	-0.422
	July	0.469	-0.204		
	August	0.438			
	September	0.443			
	October	0.476			
	November	0.474			
	December	0.413			

[a] Only values significant at $p \leq .01$ are shown.
[b] PDSI is monthly Palmer's Drought Severity Index for Oregon Climate Division 7.
[c] Bend ppt. is total monthly precipitation at climate station in Bend, Oregon.
[d] Div. 7 ppt. is total monthly precipitation for Oregon Climate Division 7.
[e] Div. 7 temp. is average monthly temperature for Oregon Climate Division 7.
[f] Year -1 is the year prior to year of tree growth.
[g] Year 0 is year of tree growth.

Hemispheric Climatic Variability

We explored the relationships between our chronology and hemispheric climatic variability by visual comparison and Pearson's correlation analysis of our chronology with ENSO and PDO indices derived from instrumental data and tree-ring climatic reconstructions. Cross-correlation functions were employed to identify lags between hemispheric climatic variation and tree growth. ENSO values were based on the historical record of the Southern Oscillation Index (SOI) (NCEP, 2001) and SOI values from a 1706–1977 tree-ring reconstruction (Stahle et al., 1998). We examined the relationship between the PDO and tree growth using monthly values of the 20th century PDO index, a measure of monthly sea surface temperature anomalies poleward of 20°N (Mantua et al., 1997), and by comparing

Table 2. Calibration and Verification Statistics for Regression Model

Period	Statistic	Results
Calibration (1930–1999, *n* = 70)	R^2	.351**
	R^2 adjusted	.342**
	Intercept	-9.051
	Slope	9.023
Verification (1900–1929, *n* = 30)	R^2	.317**
	RE[a]	0.856
	Durbin-Watson[b]	1.737*

[a] Reduction of Error (Fritts, 1976), where any positive value indicates that the predicted Palmer's Drought Severity Index values are more accurate than estimates based only on the means during the calibration period.

[b] A Durbin-Watson statistic close to 2 indicates no autocorrelation among residuals.

* $p \leq .01$.

** $p \leq .001$.

our site chronology to reconstructed sign switches in the PDO for treeline in the Pacific Northwest (Gedalof and Smith, 2001).

Species Responses to Climatic Variation

We examined the climatic response of ponderosa pine and western juniper using two strategies. First, we sought to validate our drought record by comparing it to Keen's (1937) list of extreme drought years based on his 734-year ponderosa pine tree-ring record for central and eastern Oregon. We then compared the LCF chronology to two western juniper chronologies using Pearson's correlation coefficients to assess western juniper's suitability as a climate proxy for ponderosa pine. The juniper chronologies are from the Frederick Butte and Horse Ridge sites (Holmes et al., 1982, 1983) located approximately 50 km SE and 20 km NE of LCF, respectively. These data were downloaded from the International Tree-Ring Databank (ITRDB; Grissino-Meyer and Fritts, 1997). Both juniper chronologies were compared with regional climatic records (Oregon Climate Division 7 precipitation, temperature, and PDSI) using the procedure noted above.

RESULTS

Chronology Development

Our chronology includes 35 trees and 50 cores with the largest sample depth being 46 cores (Fig. 2). The chronology extends from 1455 to 1999, a span of 545 years, with an interseries correlation of .55 and a mean sensitivity of .24. Correlation experiments show PDSI values have the strongest overall relationship with tree growth (Table 1). Bend precipitation, Oregon Division 7 precipitation, and Oregon

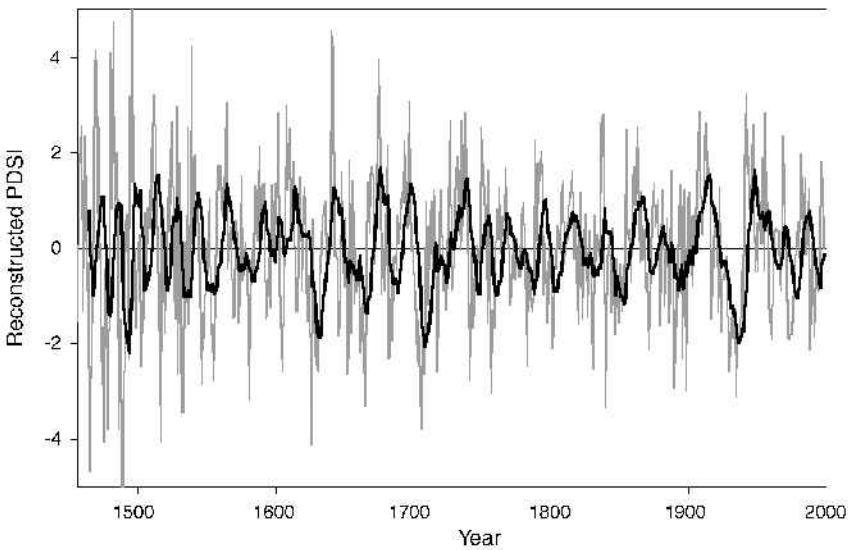

Fig. 4. Reconstructed Palmer's Drought Severity Index (PDSI), 1455–2000. Grey line is reconstruction; black line is 8-year moving average of reconstruction. Note pronounced periods of drought during the decades of 1480, 1620, 1700, and 1930.

Division 7 temperature show significant relationships with tree growth during some months, but were generally weaker than PDSI. Experiments with different aggregations of climatic variables resulted in a calibration model that included the mean PDSI during the winter (Oct–Feb) preceding tree growth and the summer (Jun–Jul) of tree growth (Fig. 3). This model explains 35% of the variance in PDSI during the calibration period (1930–1999).

The reconstructed PDSI correlation with the verification period was R^2 = .317 (Table 2). The reduction of error statistic was ±.856, indicating that the model based on the calibration period is stable and accurate. Analysis of residuals using histograms and scatterplots revealed that residuals were not correlated with PDSI and that they did not contain an autocorrelation trend. Durbin-Watson test statistics also revealed that the residuals were not significantly autocorrelated ($p \leq .01$). We used the verified, calibrated model to reconstruct PDSI from the site chronology for the entire length of the chronology (1455–1999; Fig. 4). The most pronounced drought periods in the reconstruction occurred during the decades of 1480, 1620, 1700, and 1930 with the PDSI for 1489 showing the greatest departure from normal conditions. The most sustained drought during the reconstruction period was the dust-bowl drought of the 1930s (Fig. 4). Verifications with other studies and historical records confirm the drought periods recorded in this PDSI reconstruction (Table 3). The 25 years of lowest reconstructed PDSI all correspond with years of drought or low tree growth from studies in central Oregon by Keen (1937), Holmes et al. (1982, 1983), Graumlich (1987), and/or Garfin and Hughes (1996).

Table 3. The 25 Most Severe Drought Years from 1456 to 1999 for Central Oregon, Reconstructed from Tree-Rings at Lava Cast Forest

Year	PDSI[a]	Rank	Agreement with other reconstructions[b]
1465	-4.45	3	Keen (1937)[c]
1475	-3.85	6	Keen (1937), Holmes et al. (1983)[c]
1478	-3.59	9	Keen (1937)
1486	-3.60	8	Keen (1937)
1488	-4.62	2	Keen (1937)
1489	-5.83	1	Keen (1937)[c]
1516	-3.86	5	Keen (1937)[c], Holmes et al. (1983)
1529	-2.55	23	Keen (1937)[c], Holmes et al. (1983)[c]
1532	-3.26	11	Keen (1937)[c], Holmes et al. (1983)[c]
1533	-3.27	10	Keen (1937), Holmes et al. (1983)
1546	-2.72	19	Holmes et al. (1983)
1555	-2.67	21	Keen (1937)
1626	-3.92	4	Keen (1937), Holmes et al. (1983)
1652	-2.55	24	Keen (1937)[c], Holmes et al. (1983)
1665	-3.15	13	Keen (1937)
1705	-2.67	22	
1706	-3.60	7	
1708	-2.53	25	Garfin and Hughes (1996)[c]
1741	-2.68	20	Keen (1937)[c], Graumlich (1987), Garfin and Hughes (1996)[c]
1757	-2.92	16	Keen (1937)[c]
1840	-3.19	12	Keen (1937), Garfin and Hughes (1996)[c]
1890	-2.81	18	Keen (1937)[c], Graumlich (1987)
1899	-2.87	17	Keen (1937)
1935	-2.98	15	Keen (1937), Holmes et al. (1983), Graumlich (1987), Garfin and Hughes (1996)[c]

[a] PDSI = Palmer's Drought Severity Index. Values from site chronology.

[b] Agreement with other reconstructions is within ±5 years.

[c] The year of these studies corroborates exactly with site chronology.

Hemispheric Patterns of Climatic Variability

The relationship between the site chronology and the SOI was weak. Aggregated winter months (December year -1, January year 0, and February year 0) demonstrate the greatest correlation of the observed SOI with the tree ring index ($R^2 = .09$, $p \leq .01$; Table 4). When compared to the reconstructed winter SOI by Stahle et al. (1998), no significant relationship was found until cross-correlation analysis revealed a significant, but minor relationship at a 5-year lag ($R^2 = .03$, $p \leq .01$).

Table 4. Regression Results of Southern Oscillation Index (SOI) and Pacific Decadal Oscillation (PDO) with Lava Cast Forest Site Chronology

Pattern	Record	Period	R^2
SOI	Observed DJF[a]	1900–1999	.088*
	Reconstructed DJF[a], lagged 5 years (Stahle et al., 1998)	1706–1996	.025*
PDO	Observed PDO index, lagged 6 years	1900–1999	.118*

[a] December of year-1 and January and February of year 0.
* $p \leq .01$.

The tree-ring chronology showed no direct correlation to aggregated monthly values of the PDO index. However, cross-correlation functions show that when the site chronology is lagged 3 to 9 years, significant negative relationships exist between the PDO and the site chronology, with a maximum correlation at a lag of 6 years (R^2 = .118, $p \leq .01$; Table 4). The site chronology directly reflects the three documented 20th century reversals of the PDO (1925, 1945, 1975; Fig. 5). Graphical comparison of our tree-ring chronology and tree-ring reconstructed reversals in the sign of PDO (Gedalof and Smith, 2001) shows several abrupt switches in the PDO correspond with the periodicity present in the LCF chronology (Fig. 5).

Species Responses to Climatic Variation

Comparisons of our ponderosa pine chronology with two juniper chronologies from Frederick Butte and Horse Ridge (Holmes et al., 1982, 1983) show these chronologies are weakly correlated (R^2 = .200; $p \leq .01$ and R^2 = .303; $p \leq .01$, respectively; Table 5). The two juniper chronologies correlate strongly with each other (R^2 = .560, $p \leq .01$) and have stronger correlations with climatic variables and higher mean sensitivities than our ponderosa pine chronology (Table 5). Visual comparison of our chronology with Keen's (1937) ponderosa pine-based drought record, however, reveals a high similarity between the two reconstructions. Of the most severe drought years at LCF, 11 were among the 25 most severe droughts listed in Keen's reconstruction (Table 3). Additionally, three of the most severe decades of drought in our site reconstruction (1480, 1620, and 1930) are among Keen's five most severe drought periods.

DISCUSSION

Palmer's Drought Severity Index Reconstruction

Tree growth at LCF more closely reflects aggregated measures of drought (temperature, precipitation, and soil moisture) than precipitation or temperature alone. This could be the result of two site-specific conditions. First, the root systems of these trees may reach soil moisture stored in ash and pumice deposits below the

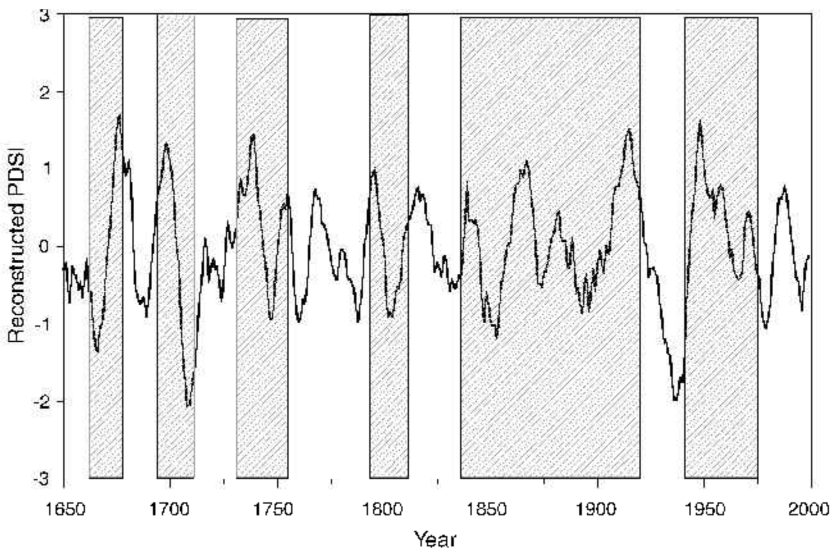

Fig. 5. Reconstructed Palmer's Drought Severity Index (PDSI; this study) and reconstructed switches in the Pacific Decadal Oscillation (Gedalof and Smith, 2001). Y-axis represents reconstructed PDSI at LCF. Any value greater than 0 indicates wetter than average conditions and any value less than 0 indicates drier than average conditions. Reconstructed PDSI is shown in 8-year moving average (black line). Reconstructed switches in the sign of PDO are shown in vertical bars. Grey bars represent negative (cool) phases and white bars represent positive (warm) phases. The beginning date of 1650 represents the initial year of Gedalof and Smith's (2001) reconstruction.

lava. Second, temperature-driven evapotranspiration rates and wind desiccation on the open lava flows may limit tree growth. Both of these factors magnify the importance of soil moisture included in PDSI, but are not accounted for in direct precipitation or temperature records. The relationship between tree growth, PDSI, and direct precipitation also indicates that precipitation and soil moisture storage during the preceding growing season and precipitation and temperature during the current growing season affect tree growth during periods of moisture and heat stress.

The mean sensitivity and interseries correlations of our chronology are low compared to some chronologies, but are comparatively high for ponderosa pine in the Pacific Northwest (e.g., Graumlich, 1987; Speer, 1997). The correlation of our reconstruction with winter and summer PDSI is also relatively high for the region (e.g., Garfin and Hughes, 1996), indicating that the reconstruction is robust. The PDSI reconstruction at LCF, however, may still be somewhat limited by the chronology's low mean sensitivity (Fritts, 1976) and by our choice to detrend our tree-ring series a second time to ensure its climatic reliability (Meko et al., 1995).

Hemispheric Climatic Variability and the Site Chronology

The site chronology from LCF is weakly correlated with the Southern Oscillation Index, explaining 9% of the variation in tree growth from 1900–1999. This weak

Table 5. Statistics for Tree-Ring Chronologies from Juniper at Horse Ridge (Holmes et al., 1983) and Frederick Butte (Holmes et al., 1982) Compared with the Lava Cast Forest Ponderosa Pine Chronology

	Horse Ridge	Frederick Butte	Lava Cast Forest
Mean sensitivity[a]	0.608	0.451	0.243
R^2 with Horse Ridge	1.000	0.560	0.303
R^2 with Frederick Butte	0.560	1.000	0.200
R^2 with Lava Cast Forest	0.303	0.200	1.000
R^2 with PDSI[b]	0.476	0.342	0.351
	(Jun–Aug)	(Oct–Sep)	(Oct–Feb, Jun–Jul)
R^2 with Bend precipitation[b]	0.293	0.375	0.155
	(Oct–Jan)	(Oct–Jan)	(May–Jul)
R^2 with Div 7 precipitation[b]	0.382	0.354	0.143
	(Oct–Feb)	(Oct–Feb)	(May–Aug)
R^2 with Div 7 temperature[b]	-0.126	-0.077*	-0.185
	(Jun–Jul)	(Jun–Jul)	(June–Jul)

[a] Mean sensitivity measures relative change between adjacent ring widths and ranges from 0 (no change) to 2 (a zero value next to a non-zero value).

[b] Correlations for Palmer's Drought Severity Index, Div. 7 precipitation, Bend precipitation, and Div. 7 temperature are for the months shown in italics and are the highest correlations with those variables. See text for details on climate variables. All values are significant at $p \leq .01$

* $p \leq .05$.

negative relationship between ENSO and tree growth mirrors the instrumental record (Taylor and Hannan, 1999) and indicates that ENSO's effect on central Oregon's climate was minor before the initiation of the instrumental record. Our results also show that a positive SOI phase (i.e., cooler, wetter La Ni a conditions) coincides with reduced tree growth in central Oregon. This seemingly paradoxical growth-response suggests other factors including the high elevation and rain-shadow location of our study site, the onset of lower regional temperatures, and the influence of continental air masses in central Oregon (Mitchell, 1976) may effectively counteract any growth benefits associated with La Ni a conditions east of the Cascades.

Although this study demonstrates the weak relationship between ENSO and central Oregon climate, this outcome is significant for several reasons. First, the long-term relationship between ENSO and central Oregon climate has not been tested before. Although teleconnections between ENSO and regional climate are not always stable (Diaz and Kiladis, 1992), our analysis suggests that the relationship between ENSO and central Oregon climate during the past 300 years has been minor, without temporal changes in direction or magnitude. Second, in other regions, ENSO has a significant influence on local forest dynamics by influencing the timing and severity of fire, insect outbreaks, and episodic mortality (e.g., Swetnam and Betancourt, 1990, 1998; Veblen et al., 2000; Kitzberger et al., 2001). This suggests other regional or local climatic patterns may be important in central Oregon and that their role in governing local and regional forest processes should be investigated. Third, ENSO generally interacts strongly with the PDO (Mantua et al., 1997). Although ENSO's relationship with central Oregon climate is minor, it may be indirectly related through the PDO, although the extent, forcing, and timing of PDO-ENSO interactions are still unclear (Linsley et al., 2000; Bitz and Battisti, 1999).

The PDO has a slightly more significant effect on tree growth than does ENSO at LCF, explaining 12% of the variation in tree growth at a 6-year lag. The PDO and the site chronology are inversely related, with tree growth decreasing during warm (positive) phases of the PDO. Central Oregon's teleconnection with PDO matches other Pacific Northwest teleconnections. The close correspondence of the sign of PDO and the site chronology in the early 20th century suggests that, while year-to-year variations in the PDO index are not detectable in the tree-ring record, lower frequency reversals in the sign of the PDO are evident. Our site chronology shows a dramatic increase in tree growth and reconstructed PDSI at each of the switches from warm to cool PDO phases identified by Gedalof and Smith (2001; Fig. 5).

Tree-Ring Reconstructions from Different Species

Based on a comparison of drought years, ponderosa pine and western juniper show a stronger within-species than between-species association. Of the 25 most severe drought years identified in the LCF chronology, 11 correspond with Keen's drought record, compared to 3 years inferred from the Horse Ridge and 0 from the Fredrick Butte chronologies (Holmes et al., 1982, 1983). The proximity of LCF to the two western juniper sites and the distances (80–240 km) separating Keen's sites further indicates that the ponderosa pine drought record is independent of local site conditions and broadly applicable to central Oregon. Several severe drought years noted in the western juniper chronologies, including 1475, 1652, and 1800 at Horse Ridge and all 5 of the years of least growth at Frederick Butte (1580, 1721, 1800, 1829, 1918), fall within +5/-5 years of major drought years identified in the LCF reconstruction. These results indicate that severe, regionally synchronous droughts appear to affect both species and all three sites similarly.

Direct correlations of tree-ring index values between the ponderosa pine chronology from LCF and the two western juniper chronologies are low, indicating notable differences in year-to-year growth of these two species. The juniper chronologies also differ from our LCF chronology in their relationship with local climatic records. Specifically, the Frederick Butte chronology is most strongly correlated to winter (Oct–Feb) precipitation at Bend, indicating that, unlike the LCF chronology, variations in direct precipitation are more important than changes in winter soil moisture. The Horse Ridge chronology showed the strongest relationship with summer (Jun–Aug) PDSI, suggesting that summer moisture stress is the most important factor limiting tree growth compared to LCF where summer moisture stress is less significant than winter soil moisture. Both juniper chronologies show relatively low correlations with summer temperature compared to LCF, suggesting high temperature stress is an important factor influencing tree growth on the lava flows.

The juniper chronologies show stronger relationships with climate than the LCF chronology, suggesting either a difference in site conditions or that western juniper exhibits greater climatic sensitivity. The similar site elevations, strong correlation between the juniper chronologies, poor correlation of the juniper chronologies with the LCF chronology, and higher mean sensitivity of western juniper chronologies (Table 5) suggests these differences are the result of different growth responses to climate. Nonetheless, a more detailed examination of environmental factors, including soil properties, seasonal snowpack, wind exposure, and the onset and duration of the growing season, may be warranted.

These results indicate that, while both ponderosa pine and western juniper reliably record regional drought years, these species respond differently to climatic variation. This suggests that studies relating fire or insect outbreak histories in ponderosa pine forests to climatic patterns derived from western juniper should be limited in their application to periods of severe, regional scale drought.

CONCLUSION

The 545-year drought reconstruction for central Oregon from ponderosa pine tree-rings shows pronounced periods of drought during the decades of 1480, 1630, 1700, and 1930. The most sustained drought occurred in the 1930s, but the most severe single drought year was 1489. Tree-growth at Lava Cast Forest is most strongly related to PDSI because it incorporates soil moisture, a critical factor for trees growing in lava. Conversely, tree-growth is weakly linked to ENSO, although indirect effects through the PDO may exist. The tree-ring chronology is significantly, but weakly linked to the PDO index at a six-year lag, indicating a weak relationship between northern Pacific climatic variation and drought cycles in central Oregon.

The Lava Cast Forest site chronology demonstrates a significant periodicity closely resembling that of the PDO, which may help us to reconstruct reversals in the PDO beyond 20th century records and to develop a better understanding of the periodicity and strength of the PDO and its relationship to central Oregon climate. While there appears to be a weak relationship between central Oregon drought and ENSO/PDO cycles, these climatic patterns deserve further investigation because of their influence on the ecology and economy of the Pacific Northwest, effects that include fluctuations of salmon populations, stream flow, hydroelectric power generation potential, and agricultural production.

Tree-ring chronologies from western juniper in central Oregon are more strongly related to local climate than our ponderosa pine chronology. Moreover, the climatic variables and seasonality controlling western juniper growth are different from those controlling ponderosa pine growth at LCF, suggesting that the two species respond differently and have dissimilar sensitivities to climatic variation or other environmental conditions.

This reconstruction extends the 20th century historical record, helping us understand the rate, magnitude, and timing of past climatic variation in central Oregon. The strength and temporal extent of this reconstruction, the first for the Newberry Crater area, helps to expand the growing network of dendroclimatological reconstructions in western North America. Previously untested in the tree-ring record, this study demonstrates that ENSO and PDO have had relatively weak influences historically on central Oregon climate. Despite these weak relationships, the location of Lava Cast Forest within a transition zone between Pacific Northwest and dry interior climatic zones suggests that central Oregon may behave as a climatic ecotone, registering changes in both regional climates and possibly acting as a sensitive climate-change indicator region. A better understanding of PDO-ENSO interactions may help us to understand the indirect effects of ENSO and the direct effects of PDO on central Oregon climate and forest processes. Specifically, research that controls for geographic differences in climate while comparing the response of different species to climatic variation is essential for the comparison of tree-ring studies. The results presented here, however, indicate that the assumption that different species respond similarly to climate may not be true. Using the same species to reconstruct both climate and forest disturbance may provide a more accurate understanding of the effects of climatic variation and climatic change on forest processes.

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