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THE DENDROCLIMATOLOGICAL POTENTIAL OF WILLAMETTE VALLEY *QUERCUS GARRYANA*

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ABSTRACT

We develop a 341-year Oregon white oak (*Quercus garryana* Dougl.) tree-ring chronology in Oregon's Willamette Valley to evaluate climate-growth relationships and determine the species' dendroclimatological potential at our site and in the surrounding region. The standardized and residual chronologies exhibit significant positive correlations with previous-year April and May temperatures, inverse correlations with previous-year spring precipitation and summer PDSI, a positive correlation with current-year July precipitation and summer PDSI, and inverse correlations with current-year June temperatures. The strength of these relationships varies over time. Significant shifts in the chronologies' mean and variance align with phase changes in the Pacific Decadal Oscillation (PDO), with lower and more variable growth during the warmer, drier positive phase of the PDO over the instrumental record. The absence of similar shifts prior to the 1900s, suggests a lack of temporal consistency in the expression of PDO variability at our site. The strong crossdating at our site reflects a cohesive climate signal, and the climate analysis illustrates the potential to develop proxy data over multiple centuries. Together, these results indicate a potential to expand the network of currently available climate proxy data by utilizing *Q. garryana* in dendroclimatological research.

Keywords: dendroclimatology, *Quercus garryana*, Pacific Decadal Oscillation, Willamette Valley, Oregon.

INTRODUCTION

Proxy data, such as ice cores, lake sediments, and annual growth rings of trees, record environmental conditions in an area over time and have been used to estimate past climates over a range of spatial and temporal scales (Fritts *et al.* 1980; Jones *et al.* 2001; Cowie 2007). In the Pacific Northwest (PNW) of the United States, tree rings in particular have been shown to be sensitive to variations in precipitation, temperature, and drought (Graumlich 1987; Earle 1993; Wiles *et al.* 1996), which are in turn influenced by coupled ocean-atmospheric processes such as El Niño Southern Oscillation (ENSO) (Rasmussen and Wallace 1983) and the Pacific Decadal Oscillation (PDO) (Mantua and Hare 2002). Understanding climate prior to the instrumental record and the factors driving climate variability can improve projections about future climate scenarios. Knowledge of past climate is vitally important to inform management of the region's climate-sensitive natural resources, such as forests, rivers, and water supplies, as well as the communities dependent upon them (Karl *et al.* 2009).

Most tree-ring research in the PNW has focused on long-lived coniferous tree species found at high elevations and on the eastern side of the Cascade Range, resulting in a data gap over much of the PNW's critical agricultural region west of the Cascades (NCDC 2013). We explore the potential for developing new proxy records at low elevations on the west side of the Cascade Range in Oregon's Willamette Valley using Oregon white oak (*Quercus garryana* Dougl.). Though it is a species of interest for conservation (ODFW 2005), it has received relatively little attention from the dendrochronological community.

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Q. garryana is a long-lived, native, deciduous tree species of the inland Pacific Coast that thrives on dry, south-facing slopes (Stein 1990), suggesting that it may be sensitive to variations in climate similar to other oak species used in dendrochronological climate reconstruction (Duvick and Blasing 1981, *Quercus alba*; St. George and Nielsen 2002, *Quercus macrocarpa*; Jacoby *et al.* 2004, *Quercus crispula*; Akkemik *et al.* 2005, *Quercus* spp.; Gervais 2006, *Quercus douglasii*; Griggs *et al.* 2007, *Quercus* spp.; Čufar *et al.* 2008, *Quercus* spp.; Meko *et al.* 2011, *Quercus douglasii*). A search of the International Tree-Ring Data Bank at the World Data Center for Paleoclimatology revealed no chronologies for *Q. garryana* (NCDC 2013). Only one published study exists regarding the dendrochronological characteristics of the species, which was conducted along its northern range boundary on Saltspring Island, British Columbia (Jordan and Gugten 2012). The lack of available data, in the context of other research utilizing oak species in dendroclimatological research, highlights an opportunity to develop new proxy records for a region lacking such data. As such, our objectives are to 1) develop a tree-ring chronology from *Q. garryana* growing in the Willamette Valley, 2) determine the climate-growth relationships exhibited by the chronology, and 3) evaluate the dendroclimatological potential of this species.

METHODS

Study Area

The range of *Q. garryana* forms a long, narrow strip that stretches from Los Angeles County, California to Vancouver Island in Canada (Figure 1a, Stein 1990). Expansion of agriculture and urban areas throughout its range has resulted in widespread losses of oak savanna habitat since the time of European settlement. Today, only 2% of the pre-settlement native oak savanna and prairie and less than 7% of the oak woodland habitat remain in the Willamette Valley (ODFW 2005; Christy and Alverson 2011). Because of its dominance prior to Euro-American settlement, research on *Q. garryana* has centered on the effects of habitat loss (MacDougall *et al.* 2004; ODFW 2005), responses to invasive and non-native species (MacDougall 2002; Devine *et al.* 2007), and the cessation of Native American burning practices (Sprague and Hanson 1946; Agee 1993; Whitlock and Knox 2002).

Our study area is Willamette University's Zena Forest and Farm located in the Eola Hills near the geographic center of the range of *Q. garryana* in the Willamette Valley of western Oregon (Figure 1a–c). Stretching approximately 210 miles south from the Columbia River to Eugene, Oregon, the Willamette Valley region is bordered by the Pacific Coast Range to the west and the Cascade Range to the east. The Eola Hills are remnants of eroded Columbia River Basalts, which are surrounded by Pleistocene flood deposits (Franklin and Dyrness 1988; Whitlock and Knox 2002). Zena Farm and Forest, a 305-acre property owned and managed by Willamette University as an educational and research facility, is located 10 mi. northwest of the city of Salem. Elevation on the property ranges from 65 to 180 m above sea level (Figure 1c). Soils are derived from sedimentary bedrock, consisting primarily of well-drained silt loams with a clayey horizon below the surface layer (Knezevich 1982). The mean annual temperature in the area is 11.7°C, while the average July and January temperatures are 19.2°C and 3.6°C, respectively (Franklin and Dyrness 1988). The valley's climate is characterized by wet winters and dry summers, with average annual precipitation of 1041 mm/yr, most of which falls between October 1 and March 31 (Figure 1d, Franklin and Dyrness 1988). Mean climate conditions at Zena Forest reflect the influences of Pacific sea surface temperatures on atmospheric circulation, with generally warmer, drier conditions during positive phases of the PDO and cooler, wetter conditions during the negative phase (Figure 1e).

The current landscape in the Willamette Valley is dominated by urban development and agriculture, although pseudo-natural habitats still exist including oak woodlands, grasslands, and conifer forests (Franklin and Dyrness 1988). Some of the first comprehensive maps of the region dating from the 1850s reveal that, prior to Euro-American settlement (*circa* 1850), the Willamette

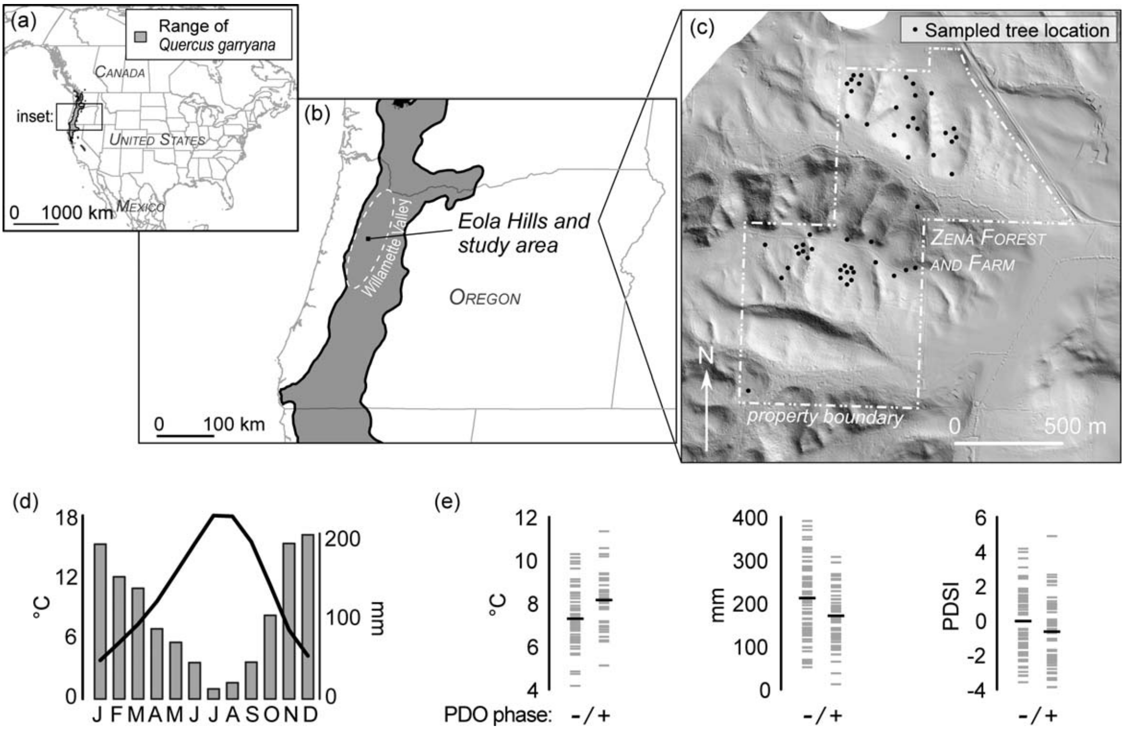

Figure 1. Study area. (a) The native range of *Quercus garryana* in North America (after USGS 2007), (b) the location of our study area within the Eola Hills of the Willamette Valley of western Oregon, (c) Zena Forest and Farm property boundaries, topography as depicted by LiDAR data for the property, and the locations of sampled trees, (d) average monthly temperature (black line) and precipitation (grey bars) at our site (NOAA 2013), and (e) temperature, precipitation (NOAA 2013) and Palmer Drought Severity Index (PDSI) (Palmer 1965) values (gray bars) and means (black bars) stratified by the cool (−) and warm (+) phases of the Pacific Decadal Oscillation (PDO) (Mantua and Hare 1997). T-tests show statistically significant differences between warm and cool phase climate variables during the winter months when the impact of PDO on PNW climate is most pronounced: mean March temperature (0.9°C, $p < 0.0005$), mean January precipitation (20%, $p = 0.0041$), and January PDSI (18%, $p = 0.0547$).

Valley was predominantly prairie, with scattered *Q. garryana* and Douglas-fir trees (*Pseudotsuga menziesii*) (Towle 1982; Whitlock and Knox 2002). This oak savanna ecosystem was maintained by frequent, low-intensity fires intentionally set by the area's Native American tribes (Whitlock and Knox 2002). After the arrival of Europeans in the region, deliberate burning ceased and most untilled areas succeeded to closed canopy forests dominated by Douglas-fir (Towle 1982; Whitlock and Knox 2002).

Chronology Development

We surveyed the Zena Forest property for large diameter oaks on south-facing slopes that displayed growth forms suggesting they were old and had grown in open conditions. Using an increment borer, we extracted increment cores along two radii of each tree between 30 cm and 1 m above the root collar, perpendicular to the slope of the terrain, and on opposite sides of the tree when possible (Speer 2010). Cores were air dried, glued into wood mounts and sanded with successively finer grits of sanding paper (220–1000 grit) to provide a polished cross-sectional surface on which individual cells could be seen with a variable-magnification binocular microscope (Stokes and Smiley 1996; Speer 2010).

Crossdating was accomplished by visually comparing cores from the same tree, and then cores among trees to identify notably wide or narrow marker rings (Stokes and Smiley 1996). Once crossdated, the annual growth increments of each sample were measured to 0.001 mm precision using a VELMEX tree-ring measuring system

(Velmex Inc. Bloomfield, NY). Crossdating was verified using the computer program COFECHA (Holmes 1983; Grissino-Mayer 2001).

We developed two standardized ring-width chronologies from the measurement series using the computer program ARSTAN v41d (Cook 1985; Cook and Krusic 2005). After inspecting the raw measurement data, the series were standardized by dividing each annual value by either a best-fit negative exponential or linear regression function or, in cases where the best-fit function had a positive slope, a horizontal line through the mean value of the series. This conservative standardization technique retained much of the low-frequency variability in growth that may be related to low-frequency climate variability such as that associated with the PDO. The index series were then combined using a robust bi-weight mean to create a standardized ring-width index (RWI) chronology. The standardized ring-width index chronology was further filtered using autoregressive modeling to remove all first-order and greater autocorrelation to produce a residual chronology that emphasized the high-frequency variability in growth associated with year-to-year changes in climate (Cook and Kairiukstis 1990).

Climate-Growth Interactions

We investigated the relationships among the standard and residual RWI chronologies and a variety of climate variables including NCDC Oregon Division 2 records of precipitation, temperature (NOAA 2013), and the Palmer Drought Severity Index (PDSI) (Palmer 1965) from 1896–2012, along with indices of the broader-scale synoptic phenomena that influence climate in the Pacific Northwest including ENSO (Rayner *et al.* 2003) and PDO (Mantua and Hare 1997). Pearson correlations over the entire instrumental record and over 20-year moving windows were calculated between the monthly climate data from the current and previous year and the tree-ring chronologies.

Because the PDO is by nature a low-frequency phenomenon with a high level of autocorrelation (and because our data consisted of a limited number of cores from one site), we did not conduct a direct analysis between our RWI and the PDO index. Instead, we compared tree growth over periods stratified by PDO phase as defined by Mantua and Hare (2002) (cool phase = 1901–1923, 1945–1976; warm phase = 1924–1944, 1977–1998), using a mean PDO index value calculated for each phase. We tested the RWI chronologies for differences in growth mean and variance between contrasting PDO phases using Student's t-tests and F-tests. Once we determined if shifts in mean or variance aligned with PDO phase shifts during the instrumental record, we applied intervention analysis (Rodionov 2004) to the standard ring-width-index chronology to determine if any changes in mean growth or variance occurred prior to instrumental PDO records. We compared the mean and variance over consecutive 20-year windows for each year of the chronology because this window length approximates the frequency of PDO regime shifts over the instrumental record and is comparable to similar analyses of PDO variability (D'Arrigo and Wilson 2006; Kipfmueller *et al.* 2012). The potential influence of ENSO was tested by correlating both chronologies to climate fields of tropical Pacific sea surface temperature using KNMI Climate Explorer (Trouet and Van Oldenborgh 2013).

RESULTS

Chronology Development

We collected increment core samples from 50 trees across Zena Forest (Figure 1c), and although multiple cores were attempted from all trees, rot often prohibited the extraction of more than one useful core. The chronologies for Zena Forest are based on the measurement series of 59 cores representing 50 trees, spanning 341 years, from 1671 to 2011 (Table 1). The expressed population signal (EPS) is >0.7 beginning in 1805 and exceeds the critical value of 0.85 from 1855–2012 (Figure 2, Wigley *et al.* 1984). However the strength of the common signal among the trees, as described by the mean series intercorrelation (r) over 50-year windows, varies over time with a sharp decline during the 1940s and 1950s, after which the common signal never approaches pre-1950s strength despite an increasing trend in the 1970s (Figure 2).

Table 1. Descriptive statistics of the *Quercus garryana* tree-ring chronology from Zena Forest, Oregon.

Total number of trees sampled	50
Number of cores	63
Number of cores crossdated	59
Series length (years)	341
Chronology interval	1671–2011
Mean series intercorrelation	0.51
Mean sensitivity	0.21
Mean length of series	139 years
Narrow marker rings (std dev >1.4, sample depth >5)	1829, 1830, 1831, 1857, 1894, 1918, 1934, 1978, 1979, 2003
Wide marker rings (std dev >1.4, sample depth >5)	1825, 1866, 1888, 1927

Climate-Growth Interactions

We used the residual chronology to identify significant correlations between the chronologies and the climate variables included in our analyses (Figure 3). When considered over the full period of analysis, the residual chronology exhibited significant positive correlations with previous-year April and May temperatures, inverse correlations with previous-year spring precipitation and summer PDSI, a positive correlation with current-year July precipitation and summer PDSI, and inverse correlations with current year June temperatures (Figure 3a).

Correlations between the ring-width chronology and climate varied over time (Figure 3b). The positive correlation between ring width and previous-year May temperatures was significant ($|r| > 0.38$, $n = 20$, $p < 0.05$) for the early and late parts of the record, but weakened from the 1940s to the late 1970s whereas the inverse correlation with current-year June temperatures has only been significant since the late 1950s. The correlation between ring-width and previous-year May precipitation was not significant early in the record but strengthened over time, and was significant from the 1950s forward. The correlation between ring width and current-year July precipitation was significant prior to the 1940s and after the 1970s. The relationships between ring width and both previous-year and current-year July PDSI were strongest early and late in the record, with weaker correlations during the 1940s to 1970s. PDO regime shifts in 1945 and 1976 generally align with some of the changes observed in these moving correlations.

Variance in both standardized chronologies was significantly different by phase of the PDO

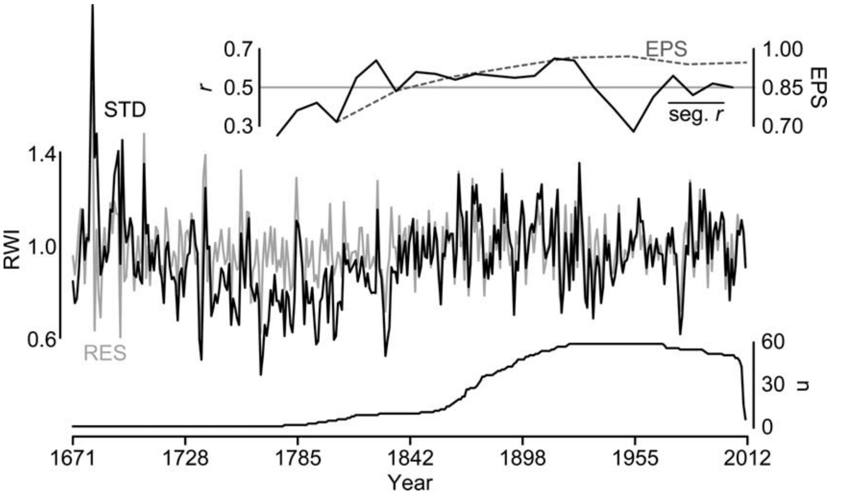

Figure 2. Standard (STD) and residual (RES) ring-width-index chronologies, sample depth (n), expressed population signal (EPS), and mean correlation (r) among all measurement series calculated over sequential 50-year windows, overlapped 25 years.

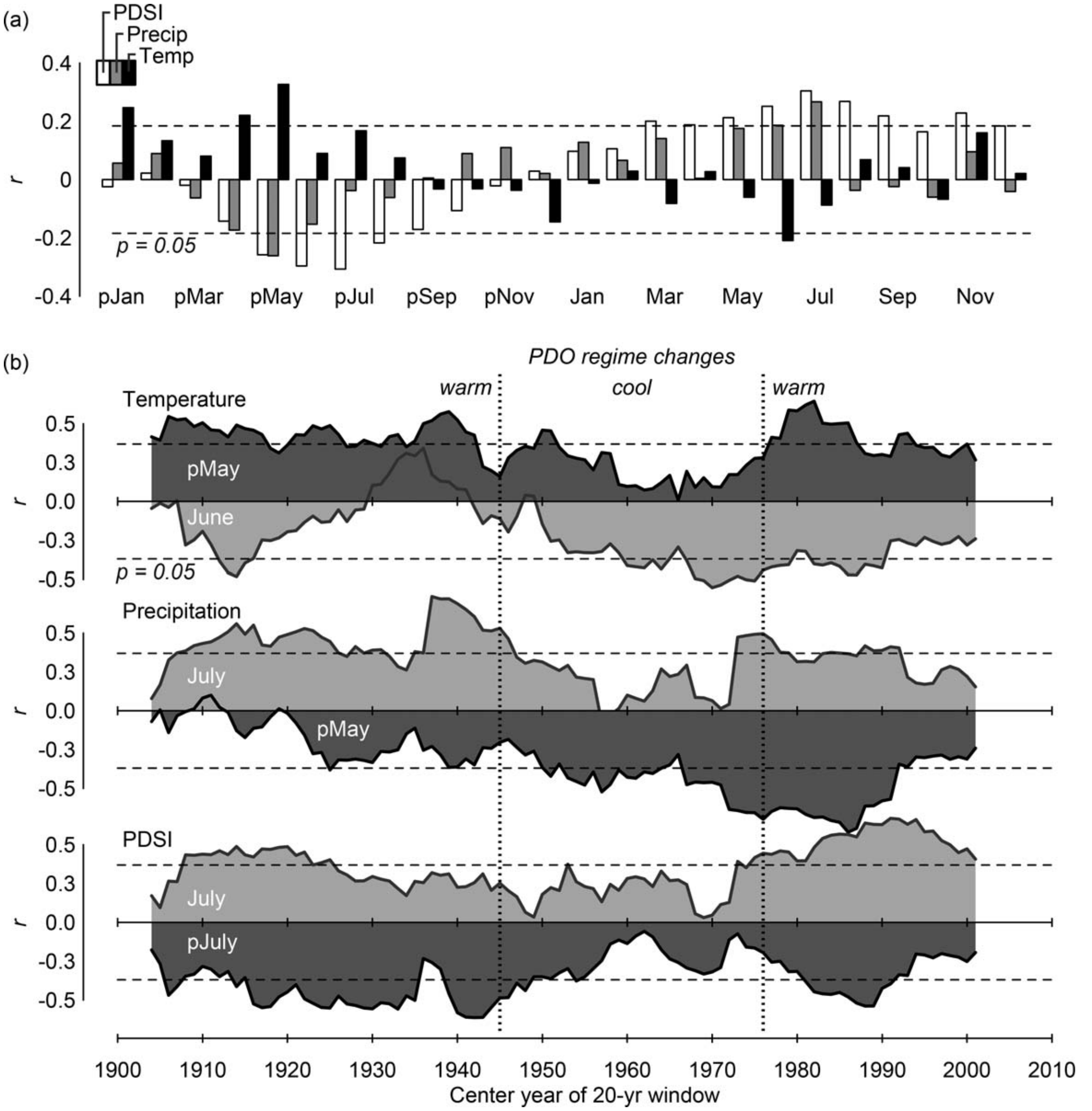

Figure 3. Correlation (r) between the residual ring-width-index chronology and monthly temperature, precipitation, and Palmer Drought Severity Index (PDSI) data over (a) the entire instrumental record (1896–2012) and (b) moving 20-year windows. Correlations were calculated from the previous January (pJan) through the current December, and only those variables showing the strongest relationships in (a) were examined over time (b). PDO phase changes are as defined by Mantua and Hare (2002).

(F-ratio ≥ 0.48, $n \geq 42$, $p < 0.01$), whereas overall mean growth showed no difference between phases ($t \leq 1.3$, $n = 67$, $p = 0.21$). During the positive PDO phase, which often leads to warmer and drier conditions for our study area (Figure 1e), the residual chronology exhibits higher variability in growth (Figure 4a), whereas the cooler and wetter conditions associated with cool phase PDO align with less variability. The correlations between our chronologies and PDSI also vary by phase of the PDO, with lower correlations for all months of the year and particularly winter months during cool phase PDO (Figure 4b). No significant relationships were observed between our chronologies and indices of sea surface temperatures or ENSO indices (data not shown). Intervention analysis

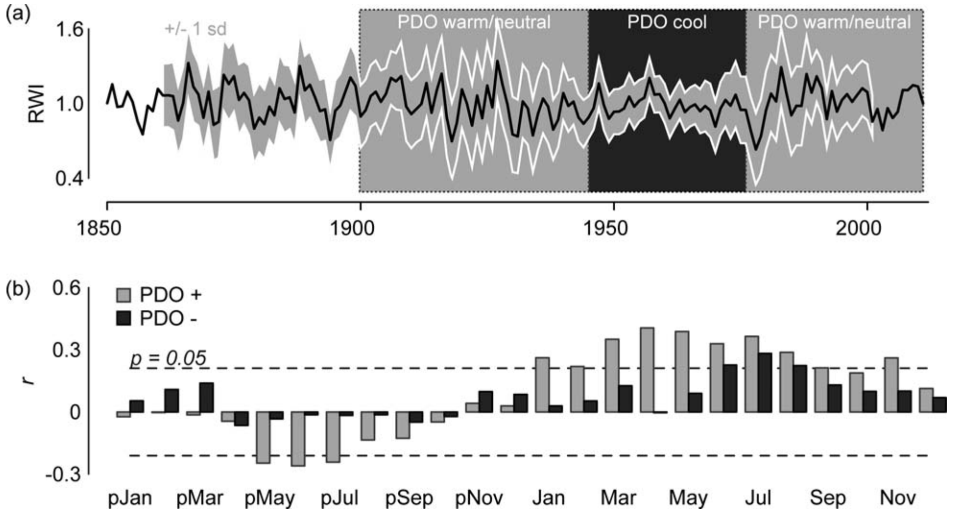

Figure 4. (a) The residual ring-width-index (RWI) chronology (black line) with standard deviation (±1 standard deviation shown as gray shading) to illustrate changes in variability by PDO phases, (b) correlations (*r*) between the residual chronology and monthly instrumental PDSI values during positive (warm) PDO (light gray) and negative (cool) PDO (dark gray) phases.

identified no shifts in the mean or variance of the standard or residual chronologies prior to the instrumental record and over the period of reliable expressed population signal (EPS > 0.85, 1855–2012; Figure 2). When the analyses were extended to the period of EPS > 0.7 (1805–2012, Figure 2), a period of decreased mean growth was identified from 1809–1835, but no shifts in variance were identified.

DISCUSSION

Our research confirms that *Q. garryana* growing in the central Willamette Valley can be used to develop robust tree-ring chronologies, but it also identifies challenges that will likely be common for dendrochronologists working with the species throughout its range. Our chronology has a lower series intercorrelation and mean sensitivity than those found by Jordan and Gugten (2012) working at the northern range limit of the species. The greater complacency we observed at our site may reflect the ecological amplitude of *Q. garryana* and overall less stressful growing conditions at our site, which is near the geographic center of the species' range. Despite the fact that these values are lower and that this chronology was developed from individuals located in the center of the species' range, we were able to successfully develop a crossdated 341-year-long ring-width chronology.

The variation in series intercorrelation over time indicates that climate is not the only major influence on *Q. garryana* growth at this site. The period of low series intercorrelation in the 1940s and 1950s aligns with a period of dramatic landscape change at Zena Forest. Historical records indicate a change in ownership of the Zena property in the early 1940s, a switch in emphasis from farming to logging, and the extensive application of scarification and planting across the property during that time. These changes could have disrupted natural landscape drivers, including hydrology, and when combined with the effects of fire suppression and exclusion that were common during that era, initiated a rapid transition toward closed-canopy conditions that is evident in forest age structure data collected in plots across the study area and historic aerial photographs. As these land-use modifications influenced stand structure, the importance of inter-tree competition and other local variables likely increased. The influence of even low-intensity human activities on the climate response of trees has been documented elsewhere (Gunnarson *et al.* 2012), as has the influence of canopy position on drought sensitivity (Orwig and Abrams 1997). The later portion of the chronology that coincides with human activity may therefore not capture as pure of a climate signal as the earlier portion of the chronology. This presents a challenge for climate-growth analyses and the development of robust climate reconstructions from this and other species that have experienced dramatic landscape changes over recent centuries.

More flexible detrending techniques have been developed for dendroclimatic research in closed-canopy forests, but our study is unique in that we are not only concerned with the potential influence of stand-scale disturbances on growth patterns at our site, but also with a fundamental change in the climate response of these trees. Furthermore, the climate of the PNW is strongly influenced by low-frequency phenomena such as PDO, and it is desirable to retain as much low-frequency variability in the tree-ring data as possible. This situation therefore emphasizes the importance of site selection, one of the basic principles of dendrochronology (Fritts 1976). Urban and rural development in the Willamette Valley has reduced *Q. garryana* populations (ODFW 2005), potentially limiting the availability of individuals old enough to provide a long-term record and constraining the number of feasible sites to conduct dendroclimatological research. Future research utilizing *Q. garryana* must balance the availability of old trees with the selection of trees that appear to be growing in relatively stable environments.

The climate response identified for our chronologies contains the classic signature of moisture limitation (positive correlations with moisture availability and inverse correlations with summer temperature), as well as an unexpected inverse relationship with prior-year spring precipitation and PDSI. The positive correlation with summer moisture availability is a common feature among trees growing in either xeric climates or on drier microsites, such as the south-facing slopes of our study area (Fritts 1976; Villaba *et al.* 1994; Tardif and Bergeron 1997; Abrams *et al.* 1998; Biondi 2000). The inverse relationship with previous spring PDSI is less common and the mechanism behind this relationship is less clear. Considered directly, our results suggest that high soil moisture conditions in the previous year reduce growth the following year. This may be explained through two factors. First, water-logged soil conditions during April–June may lead to poor soil aeration, decreasing root growth and water absorption, and ultimately reducing radial growth sufficiently to result in reduced growth the following year (Fritts 1976). Second, rather than the direct impacts of moisture on tree growth, this relationship may indicate that spring moisture availability is directly related to the duration of spring rains and their associated cool, cloudy weather. An abundance of the low, dense clouds that deliver rain to this region may reduce temperature and the amount of sunlight reaching the trees sufficiently to reduce photosynthesis (Fritts 1976). Based on our core samples, *Q. garryana* growth begins in early spring with the development of earlywood vessels. We hypothesize that regardless of the mechanism, this time of rapid growth early in the season cannot be supported from energy production during the same year because oaks tend to leaf out later in the spring (Stein 1990). Energy from the prior year is likely critical to the production of earlywood vessels at our sites. If conditions are wet and soils are water logged, or clouds reduce the amount of incoming solar radiation, the amount of energy stored by the tree to initiate growth the following year may be limited, resulting in a narrower ring.

As the causes of these climate relationships to *Q. garryana* growth are unclear, future research could assess vessel lumen area as a climate proxy for these species, a measure that has been found to be as strong as or stronger a proxy than ring width elsewhere (González and Eckstein 2003; Fonti and González 2008; Campelo *et al.* 2010). This would help deepen our understanding of the annual timing of *Q. garryana* growth and development, which would clarify the variables affecting ring patterns at different times during the year.

The relatively weak and inconsistent climate-growth relationships at our site make a climate reconstruction impractical, and although developing a broader network of sites may help overcome this limitation, we can still glean some information about past climate variability. The PDO has a pronounced impact on climate for this region. In the PNW, the positive phase manifests as drier-than-average conditions and warmer temperatures between November and April, whereas negative phases present cooler and wetter conditions during these months (Mantua and Hare 2002; Mote *et al.* 2003). The difference in PNW temperatures and precipitation between the positive and negative phases is about 1°C and 20%, respectively (Mote *et al.* 2003). These differences are also demonstrated at our site during the winter months when the impact of the PDO is most pronounced (Figure 1e). Increased variability in radial growth during the positive phase of the PDO, when our study area is warmer and drier, likely indicates more stressful conditions and a greater frequency of moisture limitation to growth. Cool phase PDO, and the associated cooler and wetter conditions, produce a steadier supply of moisture to our study area that results in less variable rings seen in our chronologies. This relationship also explains the differences in correlation between growth and PDSI during contrasting PDO phases. Therefore, although the shifting climate response limits our ability to reconstruct a specific climate variable from our chronologies, variations in the character of these time series provide insight into past PDO variability.

Although a number of tree-ring-based PDO reconstructions exist and agree over the calibration period (Biondi *et al.* 2001; D'Arrigo *et al.* 2001; Gedalof and Smith 2001; MacDonald and Case 2005; D'Arrigo and Wilson 2006), they show strong dissimilarities prior to that time (Mantua and Hare 2002; Kipfmueller *et al.* 2012). Expression of the typical PDO periodicity is also inconsistent in both instrumental and proxy records from the region (Ault and St. George 2010; St. George and Ault 2011; Kipfmueller *et al.* 2012). The patterns we identify between PDO and ring width variance suggest that, in addition to human disturbances, climatic conditions associated with different PDO phases have influenced tree growth at our site over the instrumental record. Additionally, the lack of any pattern prior to the instrumental record and over the period of reliable tree-ring data supports the literature suggesting the spatial and temporal expression of the PDO may be inconsistent in the past and that the PDO may be more of a modern phenomenon as previously indicated by other proxy records (Knapp *et al.* 2002; Ault and St. George 2010; St. George and Ault 2011; Kipfmueller *et al.* 2012).

CONCLUSIONS

This study demonstrates that Willamette Valley *Q. garryana*, despite being near the center of its geographic range, can be used to develop long chronologies with the potential to inform us about past climate variability. We show that *Q. garryana,* responds to both local conditions as well as the larger scale Pacific Decadal Oscillation, although the strength of this response varies over time. Considering that many other variables also affect the growth of *Q. garryana*, (land-use change, stand dynamics, and changing landscape patterns), future research should focus on minimizing the impacts of these factors through careful site selection. Expanding the network of available *Q. garryana* chronologies will allow for a better understanding of the growth rate of the species under varying environmental conditions and geographic gradients and has the potential to fill an important spatial gap in the available proxy data for the PNW.

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