

CLIMATIC DRIVERS OF PONDEROSA PINE GROWTH IN CENTRAL IDAHO

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ABSTRACT

Despite the widespread use of ponderosa pine as an important hydroclimate proxy, we actually understand very little about its climate response in the Northern Rockies. Here, we analyze two new ponderosa pine chronologies to investigate how climate influences annual growth. Despite differences in precipitation amount and timing and large elevation differences (1820 m versus 1060 m), ring width at both sites was strongly driven by water availability. The mid-elevation, water-limited site responded well to previous fall precipitation whereas the wetter, high-elevation site responded to growing season precipitation and temperature. When precipitation and temperature were simultaneously accounted for using the standardized precipitation evapotranspiration index, ring-width response between sites converged and appeared nearly identical. Water stress drove the timing of ponderosa pine growth by a combination of factors such as strong water dependence, and determinate growth physiology, as indicated by lag-1 autocorrelation. When analyzing response to single-month climate variables, precipitation from growing-season months dominates. When we examined seasonal variables, climate from the previous year became more important. Temporal fidelity of the climatic response at both sites maintained significance across the historical record, although the relationship weakened at the low-elevation site. The collection of new tree-ring data sets such as these for central Idaho improves our understanding of ponderosa pine growth response to climate.

Keywords: climate variability, dendrochronology, dendroclimatology, determinate growth, growth response, tree rings.

INTRODUCTION

Despite the prevalent use of ponderosa pine (*Pinus ponderosa*) in dendroclimatology studies (second only to Douglas-fir, *Pseudotsuga menziesii* in North America in the International Tree-Ring Data Bank ITRDB), we still do not fully understand the possible mechanisms controlling the variability of ponderosa pine ring-width increment in some areas of the West. Given the occurrence of ponderosa pine in low-elevation forested environments, it is generally accepted as a good proxy for hydroclimate variability (site selection principle, Fritts 1976), evidenced by its use for stream flow (Smith and Stockton 1981; Woodhouse 2001), precipitation (Graumlich 1987; Touchan and Swetnam

1995; Woodhouse 2003), and drought, *e.g.* Palmer Drought Severity Index (PDSI, Pohl *et al.* 2002; Cook *et al.* 2004) reconstructions. However, of the examples given, only Graumlich (1987), Pohl *et al.* (2002), and Cook *et al.* (2004) contain ponderosa pine data north of 41° latitude. Areas north of 41° latitude contain < 1/3 of the ponderosa pine chronologies in the ITRDB, the majority of which were originally collected for fire history or Pandora moth outbreak reconstructions and not for climatic sensitivity. In addition to the latitudinal data limitation, specific areas in the Northern Rockies of central Idaho are not represented by any ponderosa pine chronologies in the ITRDB (March 2017). To explore the possible controls on ponderosa pine ring-width variability in an understudied area, we analyzed two newly collected tree-ring chronologies for climate response and temporal fidelity.

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Multiple factors likely control ring-width variability of ponderosa pine across its broad range. Given that this species primarily occurs at warmer temperatures and lower elevations, it is typically considered to respond to water availability more than temperature, as species growing in colder temperatures and higher altitudes (e.g. *Picea engelmannii*) do (Watson and Luckman 2002; Rossi *et al.* 2008). However, the association between elevation and water sensitivity has yet to be tested everywhere in the ponderosa pine range, and there are likely differences in response because of differing climate regimes (e.g. presence/absence of the American Monsoon). Determinate growth physiology (primordial bud production representing next season's leaves based on current growing season conditions) is another factor that likely influences the response of ponderosa pine to highly variable climatic conditions, and has been famously speculated to be responsible for autocorrelation in tree-ring series (Fritts 1976). Finally, it is possible that growth response to climate will be different across the range because of the genetic variation in ponderosa pine (Knowles and Grant 1981; Potter *et al.* 2013), and the taxonomic differentiation in climatic niche between the two major sub-types (Norris *et al.* 2006).

Here, we focus on exploring the possible effects of water availability and its seasonal timing on ring-width variability. Previous work in the northern Rockies has indicated a possible bimodal response to two major precipitation regimes: previous growing season-fall response, and growing season response (Knapp and Soulé 2011). This general pattern of response has been observed for other members of the Pinaceae family, and is thought to generally reflect the importance of snowpack and the timing and availability of water when it melts. The few related publications in the Northern Rocky Mountain region of central Idaho and central Washington have hypothesized that elevation, and its influence on soil water recharge timing, is at least partially responsible for the timing of growth response. The general result is that low elevation trees respond better to previous fall-winter precipitation and higher elevation trees respond to current growing season water availability (Knutson and Pike 2008; Knapp and Soulé 2011; Dannenberg and Wise 2016). However, this pattern is not consistent. Kusnierczyk and Ettl (2002) found strong

influence of previous fall-winter precipitation from high to low elevations in northcentral Washington, and Watson and Luckman (2002) found that low-elevation ponderosa pine in western Canada tend to respond to growing season precipitation. In a large-scale study of ponderosa pine climate sensitivity, McCullough *et al.* (2017) found that the northern Rocky Mountain region exhibited some of the lowest values of climate sensitivity in the U.S. range. Thus, more detailed and thorough examinations of ponderosa pine climate response are necessary in the region to uncover the possible local and/or regional drivers of tree growth.

Understanding the climate response of long-lived trees aids in determining climate variability and change over periods extending beyond the instrumental record, but the Northern Rocky Mountains of central Idaho lacks sufficient proxy data coverage. Hundreds of kilometers separate historic ITRDB chronologies in this region, possibly because of a perceived lack of a temporally stable climate response (see Biondi 2000). Somewhat ironically, this region contains some of the largest swaths of contiguous forests in the U.S., and is composed of species important to dendroclimatological analysis (e.g. Douglas-fir, ponderosa pine, Engelmann spruce). The region is generally characterized as having a variable continental climate, with annual precipitation ranging from *ca.* 483 mm to 1520 mm per year, which is sufficiently low to contain sites where trees are limited by water availability.

In this study, we use multiple lines of inquiry to explore the specific climatic drivers on ring-width increment of northern Rocky Mountain ponderosa pine. We first conducted response-function analyses of monthly precipitation, temperature, and water stress on two newly collected ponderosa pine chronologies. Second, we use a stepwise modeling procedure to determine the most important variables for ponderosa pine growth. Third, we explicitly assessed the temporal stability of the climatic response to help further elucidate possible driving factors of growth.

METHODS

Study Area

Increment cores were collected at two sites in central Idaho, Clearwater River (SCR) and

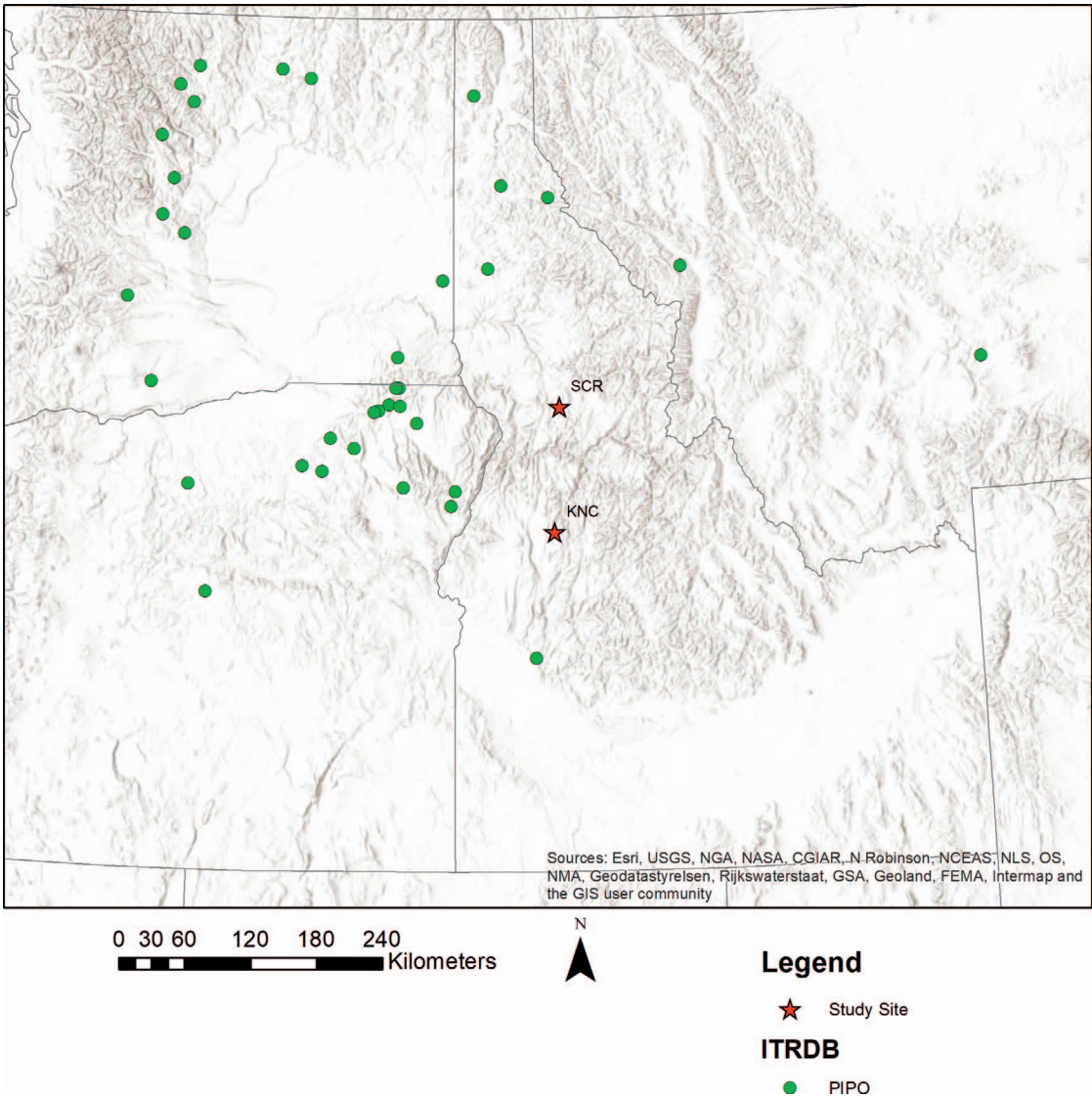


Figure 1. Regional map showing the location of two ponderosa pine chronologies in a data-poor region in central Idaho (red stars). Green dots represent ITRDB ponderosa pine chronologies.

Kennally Creek (KNC). Sites were located after extensive exploration in ponderosa pine forests, on south- and west-facing aspects that exhibited minimal soil development in a woodland-type environment where ponderosa pine was the only dominant tree species on the site. At both sites, understory vegetation was sparse and consisted primarily of pine grass (*Calamagrostis* spp). Climate at both sites was distinctly continental, characterized by cold winters, hot summers, a majority of

precipitation occurring during the winter months, and very little precipitation during July and August (PRISM, Daly *et al.* 2008). The sites, separated by *ca.* 100 km, differed in elevation, seasonality of precipitation, and total yearly precipitation (Figures 1 and 2). At KNC, precipitation was centered on the cool season, December and January, whereas at SCR precipitation peaks in May with a distinct but lesser peak in November. Water-year (October through September) precipitation was

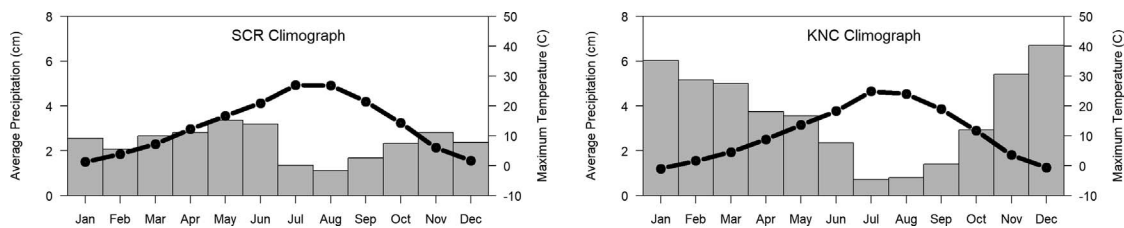


Figure 2. Climographs for two ponderosa pine sites, Kennally Creek (KNC) and Clearwater River (SCR), in central Idaho.

much higher at KNC (111.3 ± 2.0 cm) than SCR (71.8 ± 0.76 cm) (Figure 2), likely because of the elevation difference between the sites. Elevation at KNC is 1800 m a.s.l. versus 1060 m at SCR representing a generalized high and mid-low elevation site for this specific latitude based on Forest Inventory tree-ring data (DeRose *et al.* 2016) for ponderosa pine in the Northern Rockies (range 620 to 1859 m a.s.l.).

Increment Core Preparation

We collected 44 cores from 22 trees at KNC and 38 cores from 19 trees at SCR (Table 1). Increment cores were mounted to accentuate the transverse section and sanded using progressively finer grit sandpaper starting with 120-grit and ending with *ca.* 15-micron grit paper. Cores were visually crossdated under a dissecting microscope and then measured on a Velmex measuring system at 0.001-mm precision. Visual crossdating was verified at each site with the program Cofecha (Holmes 1983). We developed site-specific chronologies of indexed values using a 100-year cubic smoothing spline to detrend each series before applying a non-robust autoregressive model to remove autocorrelation. Series were averaged using the bi-weight mean. Autocorrelation found to be shared between individual trees in the chronology, and

therefore likely meaningful in a climate context (as climate can also be autocorrelated), was added back into the chronology (ARSTAN chronology). Stand-level autocorrelation maintained in the ARSTAN chronology likely reflected climate-induced growth patterns. Standardization and computation of the express population signal (EPS) statistic was completed within the program ARSTAN for Windows (Cook *et al.* 2011).

Climate Data

To examine how ponderosa pine from this region responded to climatic variability, we compared the ARSTAN chronologies to monthly and seasonal composites of precipitation, temperature, and a standardized precipitation-evapotranspiration index (SPEI), and aggregate seasons of each spanning three, six, and 12 months (see Zang and Biondi (2015) for details on aggregate season creation). We obtained average minimum and maximum monthly temperature and total monthly precipitation data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly *et al.* 2008). PRISM data came from the 4-km² grid cell centered over each site, and spanned the entire instrumental data period (1895–2014). We chose to use 4-km² pixel PRISM data because of the elevation difference between sites. SPEI, a synthetic

Table 1. Crossdating statistics for the KNC and SCR ponderosa pine sites in central Idaho.

Site	KNC	SCR
# Trees (series)	22 (44)	19 (38)
Series length (# years)	1598–2013 (425)	1603–2013 (411)
Mean series length	270.2	182.7
Series intercorrelation	0.626	0.601
Sensitivity	0.268	0.286
Autocorrelation	0.743	0.794

evapotranspiration metric that simultaneously accounts for both available precipitation and evapotranspiration during the growing season, is a scaled drought index in which positive numbers represent wet periods with lower demand for water and negative values represent dry periods when evaporative demand for water is higher. We calculated SPEI using the SPEI package (Begueria and Vicente-Serrano 2013) in R (R core team 2015). The Hargreaves (1994) method was used to estimate potential evapotranspiration in the SPEI calculation, which required the monthly maximum and minimum temperatures provided by PRISM, and estimated solar radiation using the northern latitude of the sites.

Climate Response Analyses

We anticipated that the combination of precipitation and temperature, both presumably controlling factors on growth, would result in higher correlations with ponderosa ring width. We computed correlations and partial correlations to parse the relative influence of each variable, where precipitation was the primary climatic variable and monthly maximum temperature was the secondary (Meko *et al.* 2011). As a check on the driving primary variable, we swapped the position of temperature and precipitation and reassessed significance of correlations using the seacorr function in the treeclim R package (Zang and Biondi 2015). At both sites, the variation in tree-ring width could not be adequately explained by temperature alone but was adequately explained by precipitation, and therefore we continued analyses under the assumption that precipitation was the primary driving factor. We then used SPEI to assess the combined effect of precipitation and temperature on ring width using correlation response analysis in the bootRes R package (Zang and Biondi 2013).

We further explored climate response by modelling the ability of 51 monthly and seasonally grouped variables to predict ring width at each of the sites. Multiple linear regression was used to test for significant variables that influenced ponderosa pine ring-width increment. Variables included monthly precipitation, temperature, and SPEI ranging from the previous August to September (42 variables), growing season (May–July) precipitation, temperature, and SPEI (3 variables),

water-year precipitation, temperature, and SPEI (3 variables), and a six-month precipitation, temperature, and SPEI variable ending in the previous October (3 variables for a total of 51 possible independent variables). PRISM data from the individual study sites were used to develop the suite of predictors. Results are presented as coefficients, standard errors, and t-values (parameter estimate / standard error of the estimate) for significance. Variable significance was determined with a forward, then backward, stepwise regression procedure in R based on the AIC statistic (Venables and Ripley 2002). We checked for overfitting of models with variance inflation analysis. Parameters with a variance inflation factor (VIF) ≥ 4 were considered collinear. If necessary, the least significant collinear variable was removed from the final model. To assess the temporal fidelity in ring width to climate over the historical data period (1895–2013) we calculated moving-interval correlations with the six-month averaged SPEI data. We used a bootstrapped moving-correlation analysis with a 50-year window offset by 5 years (*e.g.* window 1 = 1897–1946, window 2 = 1902–1951 ...) using the bootRes package (Zang and Biondi 2013).

RESULTS

Climate Response Analysis

Ponderosa pine tree rings at the SCR and KNC sites crossdated well (Table 1), and exhibit significant EPS for the entire series at KNC (Figure 3) and back to 1760 at SCR (Figure 4). The general pattern of response to precipitation for ponderosa pine at both sites was similar. Significant relationships occurred at one-, three-, six-, and 12-month periods centered on current growing season and previous-year cool season at SCR but only during the one-, three-, and six-month periods at KNC (Figure 5). Despite the similarities, ponderosa pine from the KNC site correlated highest with the three-month precipitation period ending in July (Pearson's $r = 0.49$), whereas ponderosa pine from the SCR site correlated highest with the three-month precipitation period ending in the previous October (Pearson's $r = 0.44$, Figure 5). Significance of partial correlations with temperature were found for KNC (the higher elevation site)

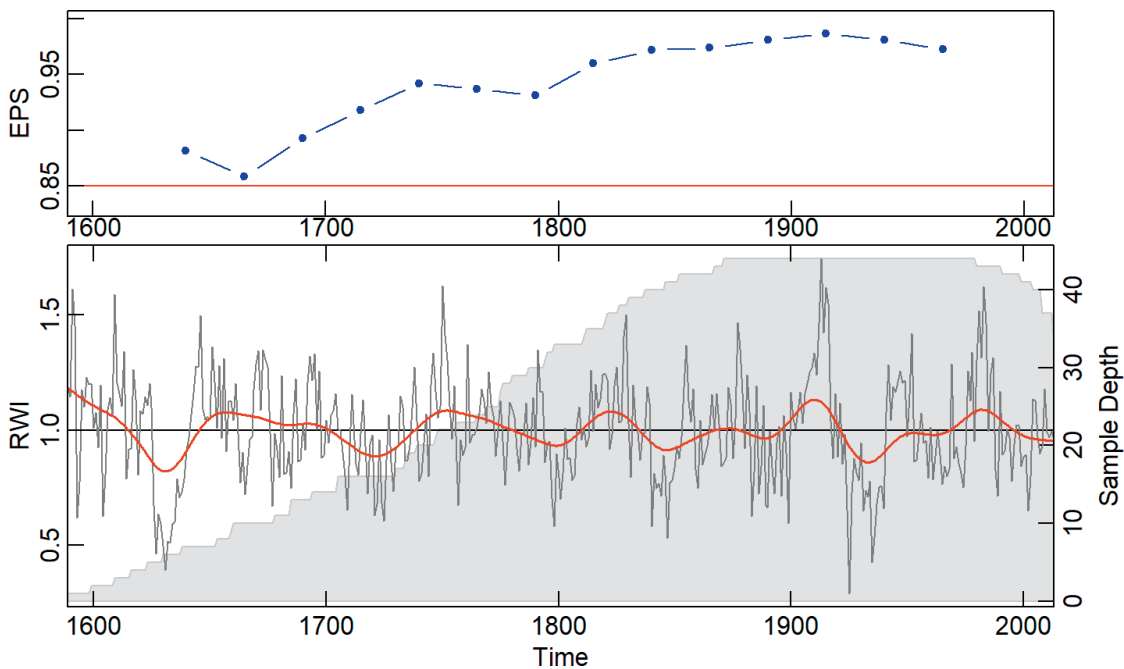


Figure 3. The ARSTAN chronology for the KNC ponderosa pine site in central Idaho displayed with a 32-year spline in red and sample depth shaded in gray (behind). Running EPS (blue with dots) is displayed with a 0.85 critical value in red.

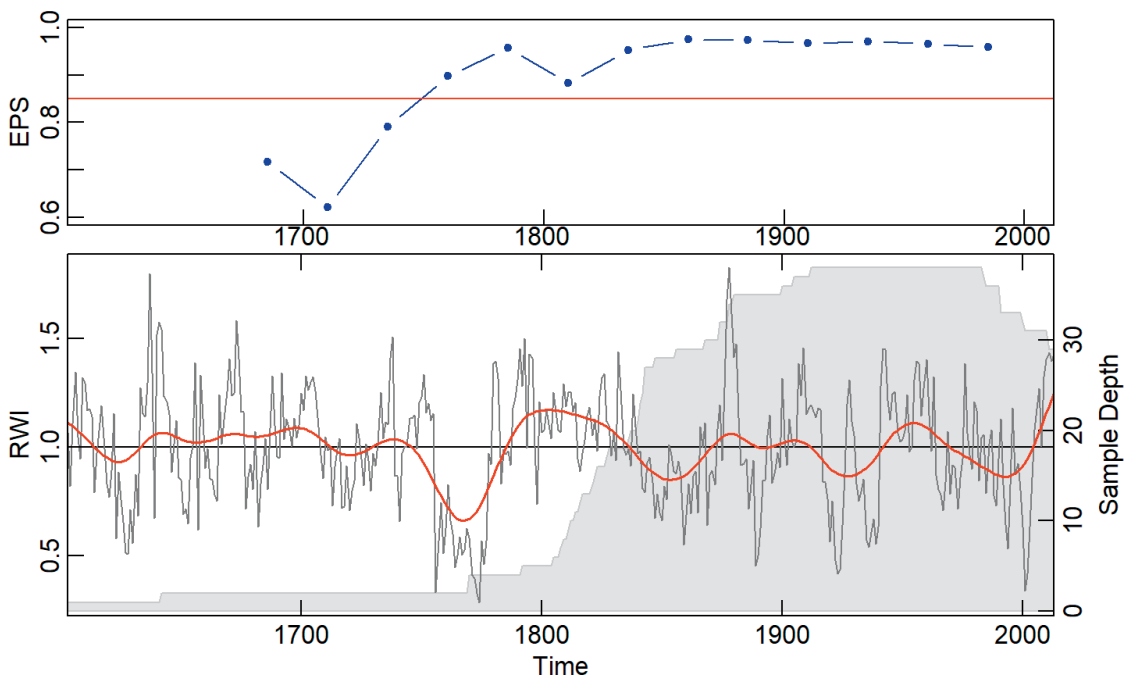


Figure 4. The ARSTAN chronology for the SCR ponderosa pine site in central Idaho displayed with a 32-year spline in red and sample depth shaded in gray (behind). Running EPS (blue with dots) is displayed with a 0.85 critical value in red.

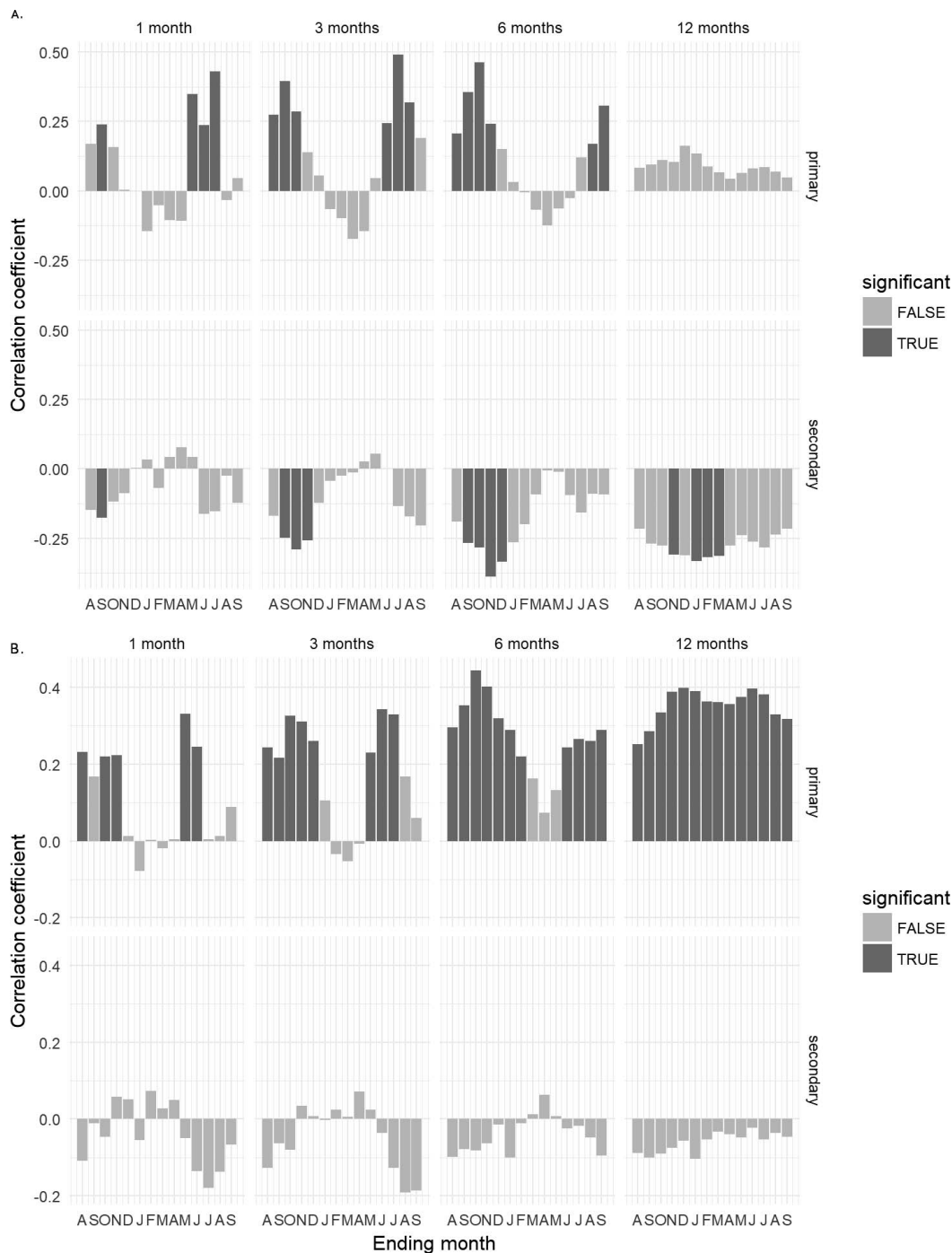


Figure 5. Correlations between the ARSTAN chronology and precipitation and partial correlations between the ARSTAN chronology and temperature at two ponderosa pine sites, (A) Kennally Creek (KNC) and (B) Clearwater River (SCR), in central Idaho. Gray bars indicate significance at the 0.05 level. Cumulative monthly total precipitation and average monthly maximum temperature values were aggregated into 3-, 6-, and 12-month seasons.

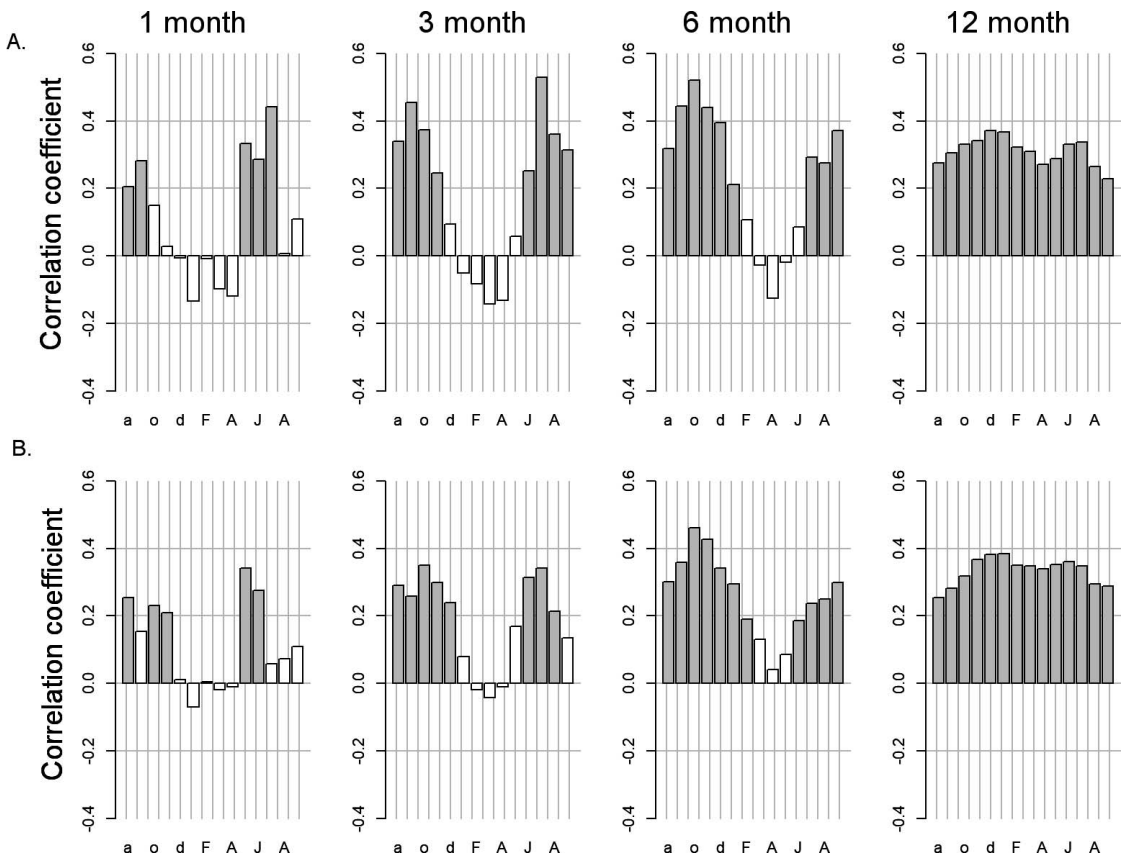


Figure 6. Correlations between the ARSTAN chronology and a calculated standardized precipitation-evapotranspiration index (SPEI) at two ponderosa pine sites, (A) Kennally Creek (KNC) and (B) Clearwater River (SCR), in central Idaho. Gray bars indicate statistical significance at the 0.05 level. Monthly cumulative SPEI values were aggregated into 3-, 6-, and 12-month seasons.

but not for SCR. Partial negative correlations with temperature at KNC were most significant during the six-month period ending in the previous November.

Ponderosa pine response to SPEI closely resembled the response to precipitation in terms of timing and magnitude. The highest correlation for KNC was for the three-month SPEI season ending in July (Pearson's $r = 0.53$, Figure 6). Second highest was for a six-month season ending in the previous October (Pearson's $r = 0.53$). These correlations were slightly higher than those found for precipitation. At SCR, the highest correlation was for the six-month SPEI season ending in previous year October (Pearson's $r = 0.46$, Figure 6). Regardless of statistical strength, when precipitation and temperature (evapotranspiration) were simultaneously considered (*i.e.* SPEI) in a response modeling anal-

ysis, the pattern of seasonal climate response between sites became virtually identical.

Multiple linear regression indicated that the most important driver of ring-width increment at both sites was the six-month SPEI season ending in the previous October, which corroborated the response-function analysis (Table 2). Of lesser importance were current growing-season SPEI and April SPEI at KNC, and May and June monthly SPEI at SCR. Collectively, the response-function analysis and the regression analysis indicated that previous-year conditions exhibited primary control on growth, and growing season conditions exhibited secondary control.

The response of ring-width to SPEI was significant over the entire instrumental record (1895–2013) for a six-month season ending in the previous October through December. At KNC, the

Table 2. Climate drivers in the final models found using stepwise regression analysis for the KNC and SCR ponderosa pine sites in central Idaho.

Site	Variables	Estimate	Std. Error	t Value	p	
KNC	Intercept	0.77	0.21	3.65	<0.001	***
	Previous 6-month warm season SPEI	0.23	0.04	5.86	<0.001	***
	Growing season SPEI	0.15	0.03	4.88	<0.001	***
	April SPEI	− 0.04	0.02	− 2.57	0.01	*
	July precipitation	0.08	0.03	2.41	0.02	*
	March temperature	0.01	0.00	2.20	0.03	*
	February temperature	− 0.01	0.00	− 1.45	0.15	
	Adj R ²	0.51				
SCR	Intercept	0.40	0.34	1.16	0.25	
	Previous 6-month warm season SPEI	0.23	0.05	5.09	<0.001	***
	May SPEI	0.08	0.02	3.90	<0.001	***
	June SPEI	0.06	0.02	2.85	0.01	**
	Previous November precipitation	0.16	0.10	1.72	0.09	
	Previous December temperature	0.01	0.01	1.71	0.09	
	January temperature	− 0.01	0.00	− 1.55	0.12	
	Adj R ²	0.35				

Note: significance is denoted with asterisks * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

six-month seasons ending in July and September were mostly significant, and the previous-year six-month seasons ending in August through December were temporally stable and significant (Figure 7). Likewise, at SCR the six-month SPEI seasons ending in the previous October through December were significant ($p < 0.05$), however, no current-season variables show temporal fidelity (Figure 7). The strength of the relationship between SCR and various SPEI season intervals begins to drop around the 1980s.

DISCUSSION

Ring-width increment of ponderosa pine from the northern Rocky Mountains was strongly driven by the quantity of both previous summer to fall and current growing-season moisture availability. At both sites, precipitation was the primary controlling climatic variable, with minimal additional information provided by temperature. However, when both precipitation and temperature were considered simultaneously (*i.e.* SPEI) the climatic response of both ponderosa pine chronologies appeared nearly identical despite the precipitation timing and elevation differences between the sites. Although SPEI attenuated the response differences between the sites, it did not explain significantly more variability in ring-width increment at either, contrary to what

we were expecting at sites with a strong continental climate limited by water stress. SCR and KNC exhibited a positive response to SPEI, which strongly mirrored their response to precipitation, generally indicating that growth suffers as water stress increases on dry southwest-facing sites.

Moisture availability was the most important variable for both of our ponderosa pine sites, corroborating what has been found for ponderosa pine regionally. Previous work in the Columbia River Basin (Dannenberg and Wise 2016), the eastern Cascade Mountains (Kusnierczyk and Ettl 2002), and western Montana and eastern Idaho (Knapp and Soule 2011) found strong relationships between hydroclimatic variables and ponderosa pine growth. Previously-documented climatic responses occurred during either the current growing season and/or the growing season and fall of the previous year. In the Columbia River Basin, lower elevation sites showed the strongest response with growing season precipitation followed by previous fall precipitation (Dannenberg and Wise 2016). In contrast, ponderosa pine in southern Oregon and the Cascades, showed consistent responses to previous fall precipitation across a gradient of high- to low-elevations (Kusnierczyk and Ettl 2002; Knutson and Pike 2008). Only in the lowest-elevation steppe ecosystem did current growing season become the second most important response variable

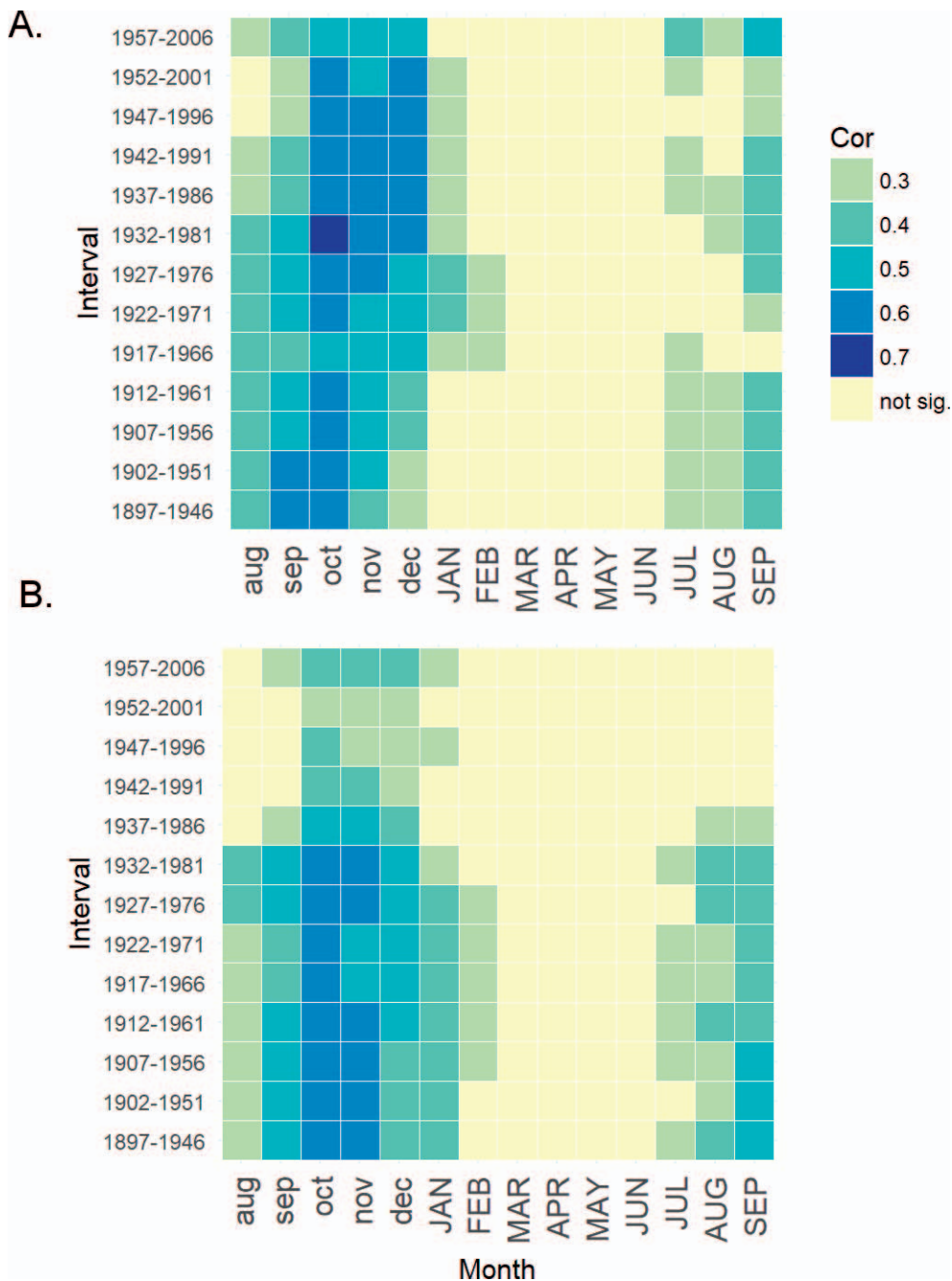


Figure 7. Moving-interval climate correlation analysis using 6-month SPEI values calculated from PRISM data for two ponderosa pine chronologies, (A) Kennally Creek (KNC) and (B) Clearwater Creek (SCR), in central Idaho. Lower-case font indicates months from the previous year. Periods significant at the 0.05 level are shaded according to their respective correlation value.

(Kusnierczyk and Ettl 2002). In the northern Rockies, both patterns were found in close proximity, with low-elevation sites showing greater response to previous fall precipitation and mid- to high-elevation sites responding to growing season precipitation (Knapp and Soulé 2011).

The mechanisms driving the timing of ring-width climatic response for ponderosa pine across the northern Rocky Mountains vary by site and study. The differing methodologies used between studies should be noted as they likely have an impact on the inferred mechanism driving growth. Certain studies used a modeling approach (e.g. Kusnierczyk and Ettl 2002; Knapp and Soulé 2011), others assessed only monthly correlations (e.g. Knutson and Pike 2008; Dannenberg and Wise 2016), and only one looked for the influence of aggregate variables as we did here (Knapp and Soulé 2011). Like all other regional studies on ponderosa pine growth, ponderosa pine in central Idaho exhibit a response to precipitation and temperature during growing season months, but by examining the influence of multi-month seasons, we show the best predictor of growth is a six-month SPEI season ending in the previous October. By assessing precipitation and temperature simultaneously (*i.e.* SPEI), the response pattern for both sites became strikingly similar, and the multiple regression analysis corroborated this result. That is, at both sites SPEI of the previous fall primarily, and secondarily the current growing season, drove growth; this is a very similar result to that of Knapp and Soulé (2011). Thus, although ponderosa pine is a good proxy for precipitation, it is likely even better at recording moisture stress (*i.e.* SPEI) in this region, especially when examining aggregate seasons influencing growth.

Because the primary control on ring width is essentially the previous growing season (May through October of previous year), ponderosa pine physiology likely plays a role in subsequent-year ring-width increment. Although ponderosa pine probably terminate xylogenesis long before September (Turner 1956), additional moisture received from August through the early fall (October) might contribute to soil moisture recharge, and thus moisture availability during the following growing season, or it may contribute to continued photosynthesis and/or root growth while temperatures allow. In

this way, late growing season precipitation may contribute to the development of next year's needles in the buds (*i.e.* determinate growth). It is possible that for determinate species the 'growing season' that contributes to the following year's flush is not necessarily constrained to the timing of xylogenesis, as other physiological processes might ultimately influence how much is 'determined' for the next year. For example, Brown (1968) showed that ponderosa pine in Arizona had high levels of photosynthesis even during winter months as long as temperatures were above freezing. Kerhoulas and Kane (2012) showed that ponderosa pine coarse root growth had the lowest correlation with water-year precipitation when compared to growth at other heights along the stem. They suggested that this might be a physiological adaptation prioritizing carbon allocation to coarse roots despite any observable soil moisture stress. Thus, whole-plant and whole-year growth physiology should be considered when determining the influence of climate on growth. Alternatively, elevation could be playing a role in climate response timing, by serving as a proxy for other, unmeasured factors (e.g. micro-site differences, aspect, etc.). However, the chronologies in this study exhibited such similar responses to SPEI that this potential influence is not assured.

It has been previously speculated that sites at high latitudes and high altitudes in North America might exhibit asynchrony in the temporal fidelity of their climatic response (Briffa *et al.* 1998; Biondi 2000; D'Arrigo *et al.* 2008). Much of this work has been done using temperature-sensitive chronologies from Alaska and Western Canada (Jacoby and D'Arrigo 1995; Briffa *et al.* 1998; Wilson and Luckman 2003; D'Arrigo *et al.* 2008). In this study, our high-elevation site (KNC) showed strong temporal fidelity to the primary (previous warm-season SPEI), and much of the secondary (current growing season SPEI) growth driver, at least as they correspond with the historical data (*i.e.* PRISM). Correlations are significant even early in the instrumental data when station data are scarce. However, our low elevation site (SCR) showed a decreasing response to both the primary and secondary growth drivers starting around the 1980s and lasting to present day. Although correlations with previous warm-season SPEI decrease over time at SCR, significance and direction remain stable. It is likely

that the six-month season of the current year contains too much spring variability to maintain significant correlations with ring width. Thus, neither site maintains significance for six-month SPEI seasons of the current year. Other studies in this area have also found some evidence of a temporally unstable link between tree growth and climate. Biondi (2000) showed temporally unstable relationships with climate, specifically drought, for dry-site Douglas-fir from central Idaho. Malanson (2017) showed changes in sensitivity for two of four high-altitude temperature chronologies in Idaho and three of six in Montana. Knapp and Soulé (2011) suggested that old trees in the northern Rockies are more likely to show increased growth from CO₂ fertilization, which may be a cause of instability for some trees in the region. However, Crawford *et al.* (2015) found temporal stability for Douglas-fir sites of Idaho and Montana. Thus, more information is needed to determine causes of temporal instability of climate growth relationships in the Northern Rocky Mountains.

CONCLUSIONS

Ponderosa pine tree rings at the SCR and KNC sites crossdated well, showed sensitivity to the regional hydroclimate, exhibited a coherent temporal response, and are an important contribution to the pool of regionally available tree-ring data. This is important for future analyses of climatology that rely on ponderosa pine, and helps assure that the implications of a lack of temporal fidelity in ring width response to climate might be limited to specific sites and species, as opposed to a characteristic of the northern Rockies, in general. Relative moisture stress on sites of ponderosa pine should be a major consideration during the process of site selection, as the physiological response of ponderosa pine to water stress has the ability to skew the strength, timing, and seasonality of climate response.

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