The Climate Response of *P. lambertiana*, *P. monticola*, and *P. jeffreyi* in Yosemite and Sequoia National Parks, California

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Abstract

This research investigates the sub-annual climate response of ten *Pinus lambertiana* and eight *Pinus jeffreyi* from Yosemite, and ten *Pinus monticola* and ten *Pinus jeffreyi* from Sequoia. We investigate the potential of using resin ducts to measure the earlywood and latewood of *P. lambertiana* and *P. monticola* and compare this growth with co-occurring, traditionally measured *P. jeffreyi*. Correlation analyses of ring widths with average monthly temperature, vapor pressure deficit (VPD), and precipitation were conducted. Our results show that the resin duct method performed poorly at both sites but better with *P. lambertiana* at Yosemite. Species at both sites generally have a positive correlation with precipitation. Earlywood and latewood correlations with climate were relatively weak. Temperature and VPD correlations were generally positive in the spring and negative in the summer months at both sites for all three species. These results reveal that future increases in temperature and VPD will leave these trees vulnerable to future droughts. More samples are needed throughout the Sierras to determine if the resin duct method can be used for sub-annual climate reconstructions, if these results can be generalized, and if sub-annual reconstructions are possible for these three species.

Keywords: tree rings, climate signal, earlywood, latewood, Sierra Nevada Mountains

Introduction

CALIFORNIA'S MAIN SOURCE of water is from precipitation in the Sierra Nevada Mountains (Jones 2015), and events such as droughts can have a profound negative effect on the state's water supply. This makes climate research imperative to further the understanding of climate variability throughout California. According to Bales et al. (2011), the Sierra Nevada Mountains account for 27 percent of the total precipitation in California, providing 60 percent of the state's total water supply. An increasingly drying climate and rising temperatures negatively impact the Sierra Nevada snowpack (Bales et al. 2011) and subsequently the state's water security. Warming temperatures will cause earlier snowmelt and more precipitation falling as rain rather than snow (Kapnick and Hall 2010), reducing the annual average snow. The year 2014 had the driest recorded soil moisture for California in the last 1,200 years and, as of fall 2021, was on track to eclipse that record (Borunda 2021; Griffin and Anchukaitis 2014). Furthermore, three years or longer droughts are common in the state of California (Griffin and Anchukaitis 2014).

Meteorological records in the Sierra Nevada Mountains are not long enough to test and capture the long-term variability of climate (Cook et al. 1999; Stambaugh et al. 2011). Tree-ring chronologies in dendroclimatology represent the climatic conditions of their location over the lifespan of the tree (Meko, Stockton, and Boggess 1995; Speer 2010), making them ideal proxies for studying climate variability. The benefit of tree-ring data is that growth rings can be accurately dated annually and, in some cases, sub-annually (Griffin et al. 2013; Leavitt et al. 2011).

Pinus lambertiana (sugar pine), *Pinus jeffreyi* (Jeffrey pine), and *Pinus monticola* (western white pine) grow in mixed-conifer forests at high elevations (300 to 3,200 meters) in the Sierra Nevada Mountains and they tend to be the dominant species in old-growth stands (Habeck 1992; Kershner et al. 2008). These species are long-lived (up to 500 years) (Gucker 2007), and their longevity makes it possible to look back over hundreds of years of climate history using dendroclimatology. Their locations are favorable because they grow in undisturbed locations, at elevations where mixed-conifer forests are exceedingly productive (Bales et al. 2011). These three species in the Sierra Nevada Mountains are relatively well studied in the tree-ring literature (Hurteau, Zald, and North 2007; Slack et al. 2017; Slack, Kane, and Knapp 2021; Stephens 2001), but they appear to be underutilized in dendroclimate studies and specifically dendroclimate reconstructions in the region. Hurteau et al. (2007) found that annual growth rings of *P. jeffreyi* and *P. lambertiana* represent climate models well at a site in the southwestern Sierra Nevada Mountains. This is despite *P. jeffreyi* having a lagged response to climatic conditions at their sample site (Hurteau et al. 2007).

Recent studies in the southwestern United States have divided annual growth rings into earlywood (EW) and latewood (LW) (Griffin et al. 2013; Leavitt et al. 2011; Meko and Baisan 2001). EW represents the formation of cells that form in the cool season (October to April), and LW represents the formation of cells that form in the warm season (June to September) and are darker in appearance (Figure 1) (Griffin et al. 2013; Meko and Baisan 2001). *P. jeffreyi* have a clear delineation in the transition from EW to LW; however, this transition is subtle

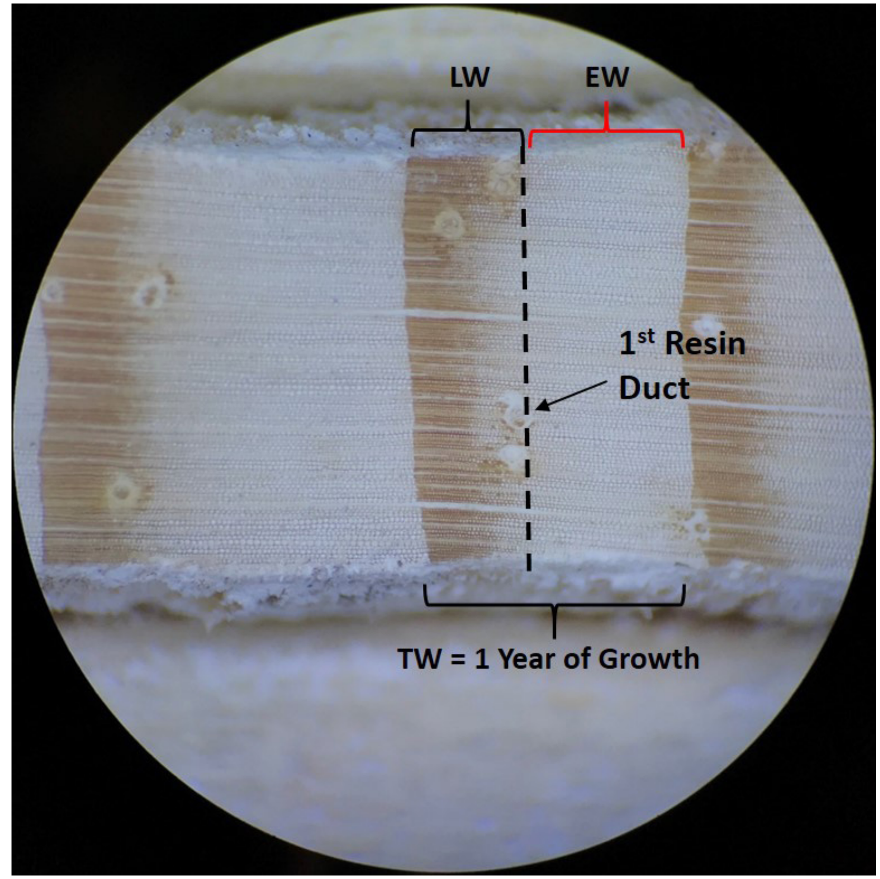

Figure 1. Earlywood (EW; black), latewood (LW; red), and the first resin duct of the ring of P. monticola dashed line represents EW/LW delineation.

and undetectable in the cells of *P. lambertiana* and *P. monticola.* This gradual change in cell colors makes it difficult to distinguish the boundary of the EW and LW, making it hard to produce sub-annual reconstructions.

Matheus et al. (2017) examined the EW and LW of *Pinus edulis* (pinyon pine) using resin ducts to delineate the EW and LW boundary and showed that EW could be used to reconstruct cool-season precipitation in *P. edulis* (Matheus et al. 2017). Resin ducts are large vertical vessels found in conifers, they are used for transporting resin which is used for protection and closing wounds (Richter et al. 2004; Werker and Fahn 1969; Wimmer and Grabner 1997). Traumatic resin ducts can form as the result of stress or a wound (fire, beetle outbreak, infection, etc.) (Bannan 1936; Nagy et al. 2000; Richter et al. 2004; Slack et al. 2017; Thomson and Sifton 1926); however, similar to *P.*

edulis, the resin ducts of most conifers form where the LW boundary begins (Richter et al. 2004; Werker and Fahn 1969; Wimmer and Grabner 1997). Duct formation along the LW boundary makes it practical to use these ducts to delineate the LW boundary in species where this boundary is not discernable (Matheus, Maxwell, and Harley 2017; Richter et al. 2004; Werker and Fahn 1969; Wimmer and Grabner 1997).

In this study, we investigate similarities in the EW, LW, and total wood (TW) ring width of *P. jeffreyi*, *P. lambertiana*, and *P. monticola*. The resin duct method is applied to measure the EW and LW ring widths of *P. lambertiana* and *P. monticola* and standard methods are used to measure *P. jeffreyi*. Because the EW/LW boundary of *P. jeffreyi* can be determined using traditional dendrochronology methods and is co-occurring with the other two species, they should exhibit the same climate response. High correlations between the ring width measurements of *P. jeffreyi* and *P. lambertiana* as well as *P. monticola* could justify the use of the resin duct method. Additionally, this is one of the first studies to examine the sub-annual climate response of *P. jeffreyi, P. lambertiana,* and *P. monticola*. This will be done by correlation analysis of tree-ring widths with existing climate data. Through these analyses we (1) determine the performance of the resin duct method in measuring the EW and LW in *P. lambertiana* and *P. monticola*, (2) learn the sub-annual climate response of each species, and (3) determine the feasibility of sub-annual climate reconstructions of each species at our sample sites.

Methods

Sample Collection

Samples for this study were collected from two sites, Wolverton (36.6°N, 118.7°W) in Sequoia National Park, and Gin Flat in Yosemite National Park (37.77°N, 119.77°W) and have elevations of 2,745 m and 2,100 m, respectively (Figure 2). Both sites receive most of their precipitation from December to March with January being the wettest period and August being the driest (PRISM 2020). In the Sierra Nevada Mountains at elevations above 1,524 m, snowpack supplies storage of water needed for forest growth in the late spring to early summer (Bales et al. 2011). This makes these locations well suited to test the resin duct method in *P. lambertiana* and *P. monticola,* as there should be a strong climate signal in the EW. *P. jeffreyi* grows abundantly at both sites, making it ideal to compare to *P. lambertiana* and *P. monticola* at Gin Flat and Wolverton, respectively (there were few *P. lambertiana* at Wolverton and no *P. monticola* at Gin Flat). Ten *P. jeffreyi* and ten *P. monticola* were sampled at Wolverton, and ten *P. jeffreyi* and ten *P. lambertiana* were sampled at Gin Flat as close to one another as possible.

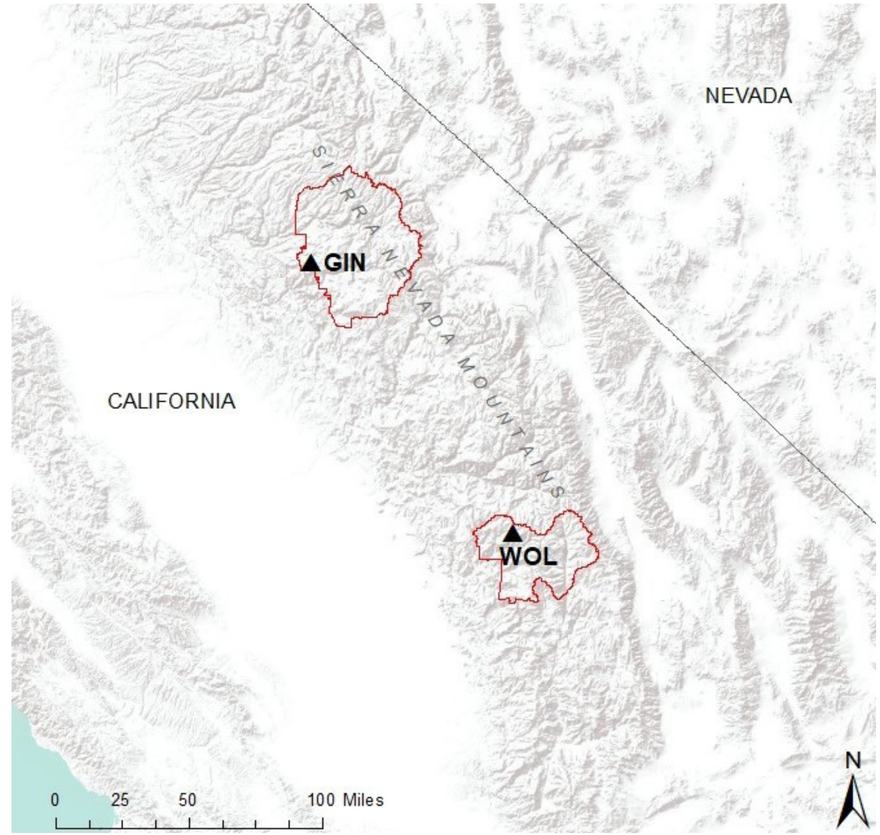

Figure 2. Tree-ring sample sites. Gin Flat (GIN) in Yosemite National Park, and Wolverton (WOL) in Sequoia National Park.

Dendrochronology methods used to collect and prepare the samples were based on procedures described by Stokes and Smiley (1996), Fritts (1976), and Speer (2010). A targeted sampling approach was used to select specific trees at each site. This approach is suitable to find older trees based on their features because samples with the most rings are desirable. Trees on a slope were targeted because of the increased likelihood of their roots being responsive to the melting snow or precipitation running down the slope (Speer 2010). Trees having visual signs of disturbance or damage (broken limbs, fire or rockfall scars, dieback or yellowing needles, etc.) were avoided to reduce the number of traumatic resin ducts produced by the tree.

Two cores were extracted at breast height (~1.2 m) from each tree using a handheld 5 mm increment bore. Both cores were taken from opposite sides of the tree, parallel to the slope to reduce the impact of asymmetrical tree growth on the rings (Fritts 1976; Speer 2010). Once extracted, the cores were placed inside individually labeled paper straws to protect and dry them, and then placed in a plastic map tube for further protection and transport.

Samples were sanded with consecutively finer sandpaper to improve the visibility of each ring, rings were counted, and the list method was used for visually cross-dating the rings (Fritts 1976; Speer 2010; Stokes and Smiley 1996; Yamaguchi 1991). Twenty cores were used for analyses for both species at Wolverton and from *P. lambertiana* from Gin Flat; however, only 16 cores were used from *P. jeffreyi* at Gin Flat due to four of the cores being damaged from heart rot or too twisted to mount correctly.

Ring Width Measurement

The transition between the EW and LW in most conifers is typically identified by a decrease in cell lumen size and an increase in cell wall thickness this results in a darker color in the ring for a given year at the EW and LW boundary (Speer 2010; Werker and Fahn 1969; Wimmer and Grabner 1997). In *P. jeffreyi*, the transition from EW to LW was easily distinguishable and could be measured using traditional methods. Unlike *P. jeffreyi,* the EW to LW boundary was not easily discernable in all the rings of *P. lambertiana* and *P. monticola*. Because the boundary was not clear, the resin duct method was implemented to potentially delineate the EW from the LW boundary in *P. lambertiana* and *P. monticola* (Matheus et al. 2017).

When measuring using the resin duct method, the first resin duct that is located in the tree ring is used to delineate the EW and LW boundary (Matheus et al. 2017). Matheus et al. (2017) found that due to the low frequency and lack of temporal pattern of rings without resin ducts, 8-14 percent (12.5 percent and 15.8 percent for *P. monticola* and *P. lambertiana* respectively at our sites), the proportion of the EW to LW was not significant to the final LW climate correlations. Thus, rings without resin ducts are divided in half for consistency across sites and species and to simplify the measurement process (Matheus et al. 2017). Each sample of *P. jeffreyi*, *P. lambertiana*, and *P. monticola* was measured under a microscope using a Velmex micrometer accurate to 0.001mm. There were a total of five missing rings between all the cores from both sites. The measurements of the TW, EW, and LW were then recorded in Measure J2X software (Voorhees 2000).

Samples were cross-dated to ensure accuracy using COFECHA (Holmes 1983). COFECHA provides an inter-series correlation that is a measure of the signal strength common to all the sampled trees at the site. COFECHA statistically verifies the tree-ring dates assigned to each core ($p < 0.01$). The biological growth trend of TW, EW, and LW for each species was removed using a cubic smoothing spline with frequency response at the 0.5 wavelength equal to 70 percent of the sample length (Cook and Peters 1981; Griffin et al. 2011). Removing the biological growth trend helps separate the lower frequency climate data from the higher frequency noise associated with forest dynamics. A ratio of the biological growth trend and the measured widths was used to create tree-ring indices for each core (Cook 1985). The influence of the previous year's growth on the current year's growth was removed from the EW, LW, and TW with autoregressive modeling (Box and Jenkins 1976; Meko 1981). The final chronologies were creating using a robust bi-weight mean for each site and species by averaging the indices for each core from each site (Cook, Shiyatov, and Mazepa 1990). Finally, the LW was adjusted (LWa) to remove the influence of the EW growth by taking the residuals of the regression of LW on EW, thus removing the dependence of the LW on the EW (Meko and Baisan 2001).

Climate Data

Parameter-elevation Regression on Independent Slopes Model (PRISM) 4 km-gridded monthly average temperature, vapor pressure deficit, and precipitation was downloaded for the closest grid to each site for 1895 to 2017 (PRISM 2020). PRISM data are created by the interpolation of individual station data and screened for use in climatological studies. PRISM data were used as there were no meteorological station data available for these remote sites. At the 4 km resolution, these data are spatially coarse. However, trees respond to climate over a much larger area than the sample sites alone, and PRISM data are also frequently used in the literature (Crawford, Griffin, and Kipfmueller 2015; Lepley et al. 2020; Meko et al. 2011). Each climate variable was correlated with the EW, LWa, and TW of the standardized chronologies using DendroClim 2002 (Biondi and Waikul 2004). DendroClim 2002 correlates the current year (t) and the previous year (t-1) monthly variables with the current year's ring widths. The previous year and current year correlations are used to show the relationship the previous year's conditions have on the current year's tree growth (Biondi and Waikul 2004). For example, a tree that is hot and stressed in the previous year will have a carryover effect into the current year. We expect there to be positive correlations for EW, LWa, and TW with precipitation. There should be positive correlations in the spring for EW and TW, with negative correlations in the summer for LWa and TW with temperature and VPD. Furthermore, the EW having the strongest correlation with climate variables in spring months and the LWa having the strongest correlation with climate variables in summer months would indicate the EW and LWa were measured correctly.

Results

Ring Width Measurement

The inter-series correlations for *P. jeffreyi*, *P. monticola*, and *P. lambertiana* chronologies are all statistically significant ($p < 0.01$, Table 1). *P. monticola* at Wolverton has the highest inter-series correlation coefficient of 0.585 ($p < 0.01$). Correlations of the TW between the species at each site were significant (Table 2), indicating that all of the species at each site respond similarly to environmental and climatic variables. However, the r-value of the correlated TW between *P. jeffreyi* and *P. monticola* at Wolverton was relatively low (r=0.241, $p < 0.05$).

All r-values of the EW, LWa, and TW between the *P. jeffreyi* (the control) and *P. monticola* and *P. lambertiana* are statistically significant, except for the LWa between *P. monticola* and *P. jeffreyi* from Wolverton (Table 2). Although the correlations are significant, they are still relatively low. The tree species at Wolverton have the lowest correlations indicating the resin duct method performed poorly at this site (EW r=0.222, $p < 0.05$; LW r=0.023, p = 0.80). EW and LW correlations at Gin Flat (EW r=0.316, $p < 0.05$; LW r=0.301, $p < 0.05$) are higher than the values from Wolverton.

Table 1. Inter-series Correlation.

Site/ Species	Number of Cores	Average Age	Inter-series Correlation*
WOMO	20	325.6	0.585
WOJE	20	196.5	0.541
GFLA	20	116.8	0.500
GFJE	16	244.5	0.517

*$p < 0.01$

Table 2. Early Wood and Late Wood Width Correlations for Wolverton and Gin Flat.

P. monticola vs. *P. jeffreyi* (Wolverton)		
EW R-values	LW R-values	TW R-values
0.222*	0.023	0.241*
P. lambertiana vs. *P. jeffreyi* (Gin Flat)		
EW R-values	LW R-values	TW R-values
0.316*	0.301*	0.401*

* $p < 0.05$

Climate Sensitivity

All seasons hereafter are defined as winter (December through February), spring (March through May), summer (June through August), and autumn (September through November).

Temperature

The correlation analyses of temperature at the Wolverton site for both species (*P. monticola* and *P. jeffreyi*) were not similar. Unlike *P. jeffreyi*, the LWa for the *P. monticola* did not correlate and had no signal for temperature. The year 2021's late summer temperature positively correlates with the EW, LWa, and TW of the *P. jeffreyi* (Figure 3). There are positive correlations for the EW and TW of the *P. monticola* for spring 2021.

The correlation analysis with temperature at Gin Flat for both species (*P. lambertiana* and *P. jeffreyi*) are comparable. Both species have negative correlations for the EW and TW in the spring 2020 (Figure 3). *P. jeffreyi* has a negative correlation in 2020's late summer and autumn seasons for its EW and TW. The correlation then shifts into a positive correlation for the EW and TW in winter 2020. There is no correlation between the LWa of *P. jeffreyi* for the temperature at Gin Flat, and *P. lambertiana* only showed a weak positive correlation for November 2021 and a weak negative correlation for March 2020.

Vapor Pressure Deficit

The correlation analysis of VPD at Wolverton for both species was not similar. *P. jeffreyi* had positive LWa correlations scattered throughout 2020 and 2021 (Figure 4). The only negative correlations for *P. jeffreyi* was for late spring 2020 for the EW and June 2021 for the EW and TW. *P. monticola* has mostly negative correlations with VPD, except for a positive correlation in spring 2021 for the EW and TW.

At Gin Flat, both *P. jeffreyi* and *P. lambertiana* have similar correlations. Both have negative correlations for 2020's spring months for the EW and TW (Figure 4). These negative correlations are also similar for both species in the 2020's spring months for the EW and TW for temperature. One significant difference between the climate responses for both species at this site is that *P. jeffreyi* had stronger negative correlation values overall than *P. lambertiana*.

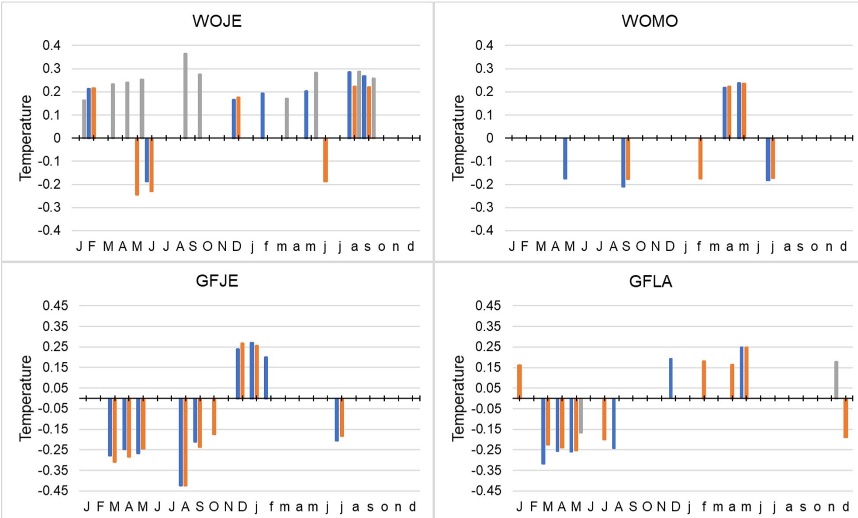

Figure 3. Significant correlations ($p < 0.05$) of monthly temperature correlations (uppercase = previous year; lowercase = current year) of the EW (orange), LWa (gray), and TW (blue) of P. jeffreyi *(WOJE top left) and* P. monticola *(WOMO top right) at Wolverton, and of* P. jeffreyi *(GFJE bottom left) and* P. lambertiana *(GFLA bottom right) at Gin Flat.*

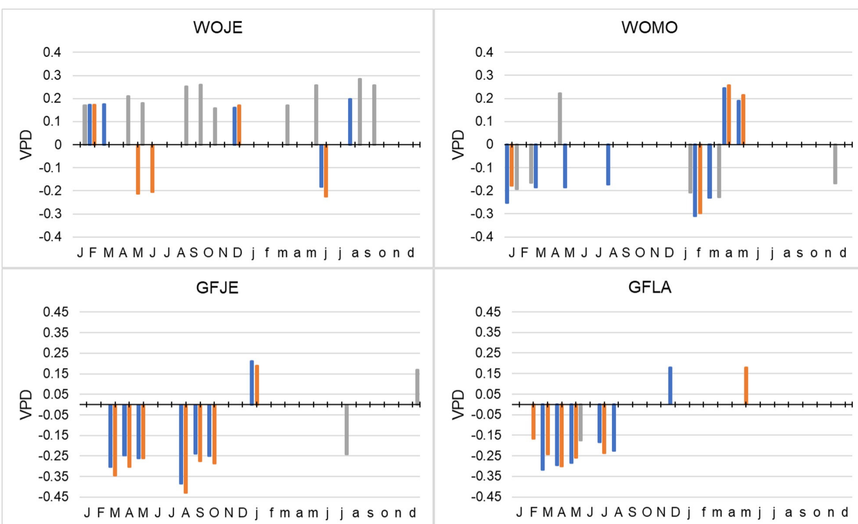

Figure 4. Significant correlations ($p < 0.05$) of monthly vapor pressure deficit correlations (uppercase = previous year; lowercase = current year) of the EW (orange), LWa (gray), and TW (blue) of P. jeffreyi *(WOJE top left) and* P. monticola *(WOMO top right) at Wolverton, and of* P. jeffreyi *(GFJE bottom left) and* P. lambertiana *(GFLA bottom right) at Gin Flat.*

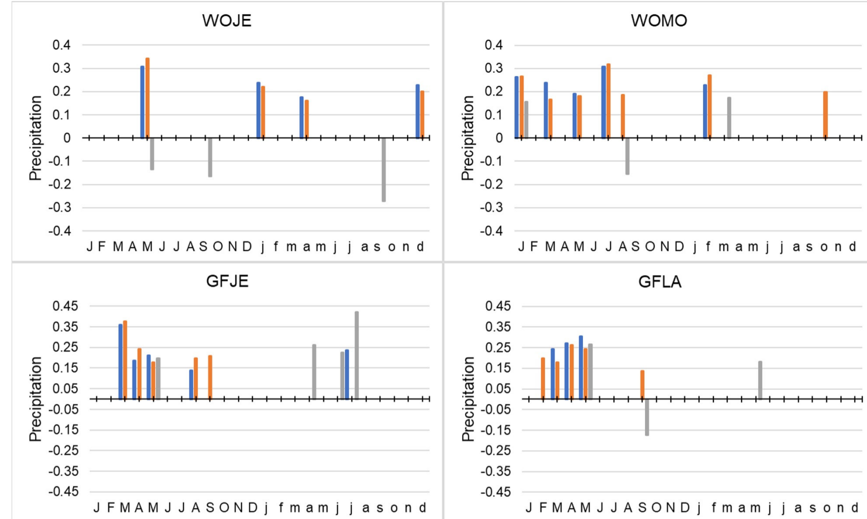

Figure 5. Significant correlations ($p < 0.05$) of monthly precipitation correlations (uppercase = previous year; lowercase = current year) of the EW (orange), LWa (gray), and TW (blue) of P. jeffreyi *(WOJE top left) and* P. monticola *(WOMO top right) at Wolverton, and of* P. jeffreyi *(GFJE bottom left) and* P. lambertiana *(GFLA bottom right) at Gin Flat.*

Precipitation

The correlations between precipitation and ring widths at Wolverton were positive for both species, except for a few LWa ring widths that negatively correlated with precipitation. However, the only comparable correlations between the two species were the positive correlations with the EW and TW widths in March 2020 (Figure 5). Positive correlations for the EW and TW in *P. jeffreyi* were in 2021's January, April, and December (Figure 5). The precipitation correlations for *P. monticola* were positive for the EW and TW and scattered from winter through early summer.

The precipitation correlation analyses between *P. jeffreyi* and *P. lambertiana* at Gin Flat were positive and similar. The year 2020's spring months influence the EW and TW positively for both species, with the LWa additionally being influenced in May for both species (Figure 5).

Discussion

Ring Width Measurement

EW and LWa width correlations derived from measurements utilizing the resin duct method indicate that the resin duct method should not be used to measure the EW and LW for *P. monticola* at Wolverton. Because the EW and

LW widths rely on the boundary between the EW and LW being accurately delineated, we can't be certain that the EW or LW was properly measured as the LWa correlations were not significant between the species. The resin duct method was more effective for the *P. lambertiana* sampled in Gin Flat with similar results as Matheus et al. (2017).

Two plausible explanations for the low correlations at Wolverton are (1) the sample site is too spread out for species to be considered co-occurring, and (2) resin ducts in *P. monticola* did not form along the EW/LW boundary. Trees at Wolverton were spread over a large area with clusters of *P. monticola* and *P. jeffreyi* being somewhat disjunct. Due to the size of the site, there was a difference in elevation between the two species. *P. monticola* were sampled at 3,049 m and *P. jeffreyi* were sampled at 2,134 m. Additionally, due to the site being along Kings Canyon, the *P. monticola* were sampled on a steeper slope and were less densely populated than *P. jeffreyi*. Consequently, these species are not experiencing the same common growth signal and therefore cannot necessarily be considered co-occurring species.

The results suggest that the resin duct method may be valid for measuring EW and LW ring widths of *P. lambertiana* at Gin Flat. *P. lambertiana* measurements significantly correlated with those of *P. jeffrey*i. These results were similar to Matheus et al. (2017). However, our correlations were lower. The low correlations at Gin Flat in this research could be attributed to resin ducts forming as a result of damage to the pines (fires, beetles, etc.) and would thus cause the boundary between the EW and LW to be erroneous. Damage occurring to the tree in the early to middle of the growing season could lead erroneously to the assignment of the EW/LW earlier in the ring (Matheus et al. 2017). A larger sample size would help reduce the impact of traumatic resin duct formation as it is not likely that every tree would be damaged in a given year.

Climate Sensitivity

There were various responses to climate in the EW, LWa, and TW for *P. jeffreyi* and *P. monticola* sampled at Wolverton. However, these signals were not comparable, which is expected due to the low correlation coefficients between the species of the EW and LW ring widths. At a minimum, we would expect the TW climate response to be consistent for both species since the methods for measuring the TW for both species were the same; however, this was not the case. These inconsistencies make it difficult to understand the limiting factors of growth at the Wolverton site. This is further evidence that Wolverton should be treated as two separate sites, one for *P. jeffreyi* and the second for *P. monticola*.

The climate response for *P. jeffreyi* sampled from Wolverton has a mix of negative and positive correlations. These correlations are sporadic between each month making it difficult to interpret the results. It does seem as though sub-annual data can be extracted from *P. jeffreyi* as the LWa has a stronger climate signal (temperature and VPD) in the summer months when LW is typically added than the EW and TW. However, this is not the case in the spring months for all of the variables as the EW does not have the strongest signal. This is likely due to an issue in site selection. The *P. jeffreyi* were all sampled on a gentler slope than *P. monticola*, making it difficult to determine a limiting factor (Speer 2010). If the slope is not steep enough the roots could have access to water resources year-round (Speer 2010).

The climate response results for *P. monticola* are not easily interpreted. Unlike *P. jeffreyi*, there are no physically meaningful climate signals associated with LWa in the summer months, further indicating that the resin duct method performed poorly with *P. monticola* at Wolverton. Temperature and VPD correlations with EW and TW are mostly negative at Wolverton until the spring. This could indicate that in the future, years with higher winter temperatures and subsequently higher VPD will stress the trees and negatively affect the available soil moisture for spring growth (Ficklin and Novick 2017). Similarly, Temperature and VPD are in synch in April and May with positive correlations. This potentially supports the importance of the timing of spring temperatures for ending dormancy at higher elevations (Barnett et al. 2008; Zhang, Friedl, and Schaaf 2006). Future reconstructions, if any, should only use the TW for *P. monticola* at this site.

Temperature and VPD correlations with LWa are not prevalent for either of the species at Gin Flat. These findings imply that temperature and VPD are not important to the LW growth for both species at this site, a contrast from previous sub-annual climate studies (Griffin et al. 2011; Matheus et al. 2017; Meko and Baisan, 2001; Leavitt et al. 2011). *P. lambertiana* and *P. jeffreyi* have negative correlations for temperature and VPD between EW and TW ring widths. Indicating that these trees are potentially vulnerable to increasing winter and spring temperatures. Ficklin and Novick (2017) found that increasing temperatures will increase VPD and adversely affect forest health.

Precipitation has positive correlations with EW, LWa, and TW. The LWa is more responsive to precipitation in both *P. jeffreyi* and *P. lambertiana* than Temperature and VPD at Gin Flat. The stronger significant correlation of *P. lambertiana* EW width with precipitation indicates that this species can be used for cool-season precipitation reconstructions; these results are similar to the findings in Matheus et al. (2017). Additionally, these results generally show stronger EW correlations in the spring months than LWa and TW and stronger correlations of LWa in the summer months than TW and EW for both species. This further supports the feasibility of using traditional methods for measuring the EW and LW in *P. jeffreyi* and the resin duct method for measuring the EW and LW in *P. lambertiana*.

Conclusion

This study examined the efficacy of the resin duct method on *P. monticola* and *P. lambertiana* in comparison with co-occurring *P. jeffreyi* for identifying the climate response and creating sub-annual reconstructions of climate variables at two different sites in the Sierra Nevada Mountains. The insignificant EW, LWa, and TW correlations between traditionally measured *P. jeffreyi* and *P. monticola* measured with the resin duct method indicate that method performed poorly at Wolverton. Additionally, correlations of climate variables with ring widths indicate that the two species were responding differently to the climate. Further, consideration of the Wolverton sample site coupled with these results suggests that these two species are not truly co-occurring. These findings make it impossible to verify that the resin duct method can be applied to *P. monticola* at Wolverton and thus not useful for sub-annual climate reconstructions.

The results suggest that it is possible to use the resin duct method for delineating the EW and LW boundary in *P. lambertiana* at Gin Flat. Correlations between the EW, LWa, and TW of traditionally measured *P. jeffreyi* and *P. lambertiana* measured using the resin duct method were significant, albeit relatively weak. The strongest climate signal occurred between EW and precipitation for both *P. jeffreyi* and *P. lambertiana*, indicating that a sub-annual precipitation reconstruction using the EW could be feasible.

The EW had a stronger spring climate signal than LWa and TW, and the LWa had a stronger summer signal than EW and TW, for *P. jeffreyi* at both sites and *P. lambertiana* at Gin Flat. This is further evidence that the EW and LWa were measured properly (for *P. jeffreyi* at both sites and *P. lambertiana* at Gin Flat) because we would expect the spring climate to affect the EW as it grows in the spring and the summer climate to affect LW growth as it is added in the summer. The results indicate that *P. jeffreyi* could be used for sub-annual reconstructions, but the climate signal is not the same at both sites. Further sampling of *P. jeffreyi* throughout the Sierra Nevada Mountains is needed to generalize the limiting factors for the species.

The response of *P. jeffreyi* and *P. lambertiana* at Gin Flat as well as *P. monticola* from the Wolverton site with temperature imply that future increases in temperature and associated increases in the VPD coupled with a higher frequency of drought could have a profoundly negative impact on the species at these sites. Additionally, the negative correlations of temperature and VPD in 2020's growth for these species could indicate that it can take longer than a year to recover from drought.

In the future, more samples of *P. monticola* and *P. jeffreyi* located closer together could clarify the sub-annual climate response of *P. monticola* and determine with reasonable certainty if the resin duct method works. Additionally, more samples should be collected for analysis as this will likely improve the correlation values and strengthen the argument that the resin duct method is feasible for *P. monticola* and *P. lambertiana*. Samples should be collected at more sites in the Sierra Nevada Mountains to determine if the resin duct method can broadly be used for measuring the EW and LW in *P. lambertiana.*

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