

TREE GROWTH RESPONSE TO CLIMATE CHANGE ACROSS THREE  
CONIFER SPECIES IN A NAVAJO FOREST

By

MELISSA RENEE SCHWAN

---

A Thesis Submitted to The Honors College

In Partial Fulfillment of the Bachelors degree  
With Honors in

Geosciences

THE UNIVERSITY OF ARIZONA

DECEMBER 2016

Approved by:

---

Dr. Kevin J. Anchukaitis  
Department of Geosciences

## **Acknowledgments**

This research was made possible through funding from the Navajo Nation (joint agreement CO1142). Permission to collect samples and to carry out research on Navajo land was granted by the Navajo Forestry Department and the Navajo Historic Preservation Office (#C14028). I want to thank Chris Guiterman and Kevin Anchukaitis for their mentorship throughout this project. Many thanks to Chris Baisan, Royale Billy and Pat Brewer, for their role in sample collection, and for their help dating and measuring the cores. A. Park Williams provided us with climate data. Lastly, a heartfelt thanks goes to Jordan Krcmaric for his unwavering support.

## Abstract

Conifer forests in the Southwest are predicted to be particularly at risk from increased drought and higher temperatures projected for the region. Higher temperature in the Southwest leads to higher evaporative demand, exaggerating drought effects, and under extreme conditions can stress trees to the point of mortality. Severe droughts are also a well-documented driver of tree-killing forest disturbances, including wildfire and insect outbreaks. Regional projections of forest drought stress show heightened sensitivity of tree growth and disturbances to hotter droughts. Little is known about how future droughts might manifest at landscape and finer scales or among different species. Understanding these dynamics is crucial for management. Here we present a multi-species, multi-variate analysis of tree response to climate at two sites on the Navajo Nation where *Pinus edulis*, *Pinus ponderosa*, and *Pseudotsuga menziesii* are co-occurring. We tested tree growth patterns from standardized chronologies and basal area increment against a high-resolution PRISM climate dataset. We found similar responses to climate at annual and seasonal scales across species, and although species varied in growth rates, growth was synchronous in severe drought years. These findings suggest that at these sites, all three conifer species will likely respond in equivalent ways to future hotter droughts.

## 1. INTRODUCTION

Conifer forests in the southwestern United States (Southwest) are predicted to be particularly at risk from increased drought and higher temperatures projected in the region (Allen, *et al.*, 2010, Allen, *et al.*, 2015). Climate models show a clear upward trend in regional temperature, but there is less confidence in precipitation trajectories, owing to major uncertainties in the dynamics of the North American monsoon. Nonetheless, higher temperature will increase atmospheric evaporative demand, enhancing moisture limitations and heat stress to trees. These effects, in combination with projected rates of severe forest disturbance processes, which are also highly temperature driven, highlight the vulnerabilities of southwestern conifers to future extreme drought conditions.

In the Southwest, drought is common; the forests of this region have experienced a long history punctuated with deep and long-lasting droughts. The conifer species in the Southwest are therefore well-adapted to drought. However, with increased temperature and its effects on atmospheric moisture demand, these species may be increasingly susceptible to drought.

With projected warmer temperatures in the region, it is predicted that there will be more hot droughts, which will put more evaporation stress on trees (Weiss, *et al.*, 2009). This makes it crucial that ecosystem managers understand how factors such as the ones mentioned here play out in forests. More importantly, these dynamics must be understood on the scale at which these forests are managed. Many trends of increased drought stress and tree mortality are based on broad patterns that result from regional studies (Williams, *et al.*, 2010). While these broad overall trends are understood with

some certainty, there is still much to be learned about the dynamics of drought, disturbances, and tree mortality at finer spatial scales. For example, different species have their own suite of adaptations to climate, drought events, and disturbance, which determines its ecological niche and range. We are interested in whether different conifer species in the Southwest respond differently to recent climate changes.

There have not been many evaluations of climate response among different species where site conditions such as elevation, soil type, soil moisture, slope aspect and angle are controlled. In general, different species have been evaluated across different environments, based in part of where they have been historically sampled.

Our study is therefore unique in that we analyze two sites at mid-elevation where three conifer species, piñon (*Pinus edulis*, PIED), ponderosa (*Pinus ponderosa*, PIPO), and Douglas-fir (*Pseudotsuga menziesii*, PSME) are cohabitant. By naturally controlling for site-level differences, we can evaluate species responses to climate with results that are not confounded by those factors. PSME, which generally occurs at higher elevations and on mesic sites may not be as well-adapted to drought as PIPO and PIED. This gives us the opportunity to investigate whether there is a difference in PSME productivity and response to drought.

In this study, we use high-resolution gridded climate data and dendrochronological data to answer the following questions.

1. Are the three species at these sites responding differently to climate?
2. Are there differences in tree productivity between the species at these sites?

Specifically, does Douglas-fir show some signs of growth stress?

3. How has recent upward trending temperature-driven atmospheric moisture affected these three species?

## **2. METHODS**

### **2.1 Study Area**

My sites are located on the Defiance Plateau, near the Arizona-New Mexico border (Figure 1). The Defiance Plateau is bounded on the north by the canyons of Canyon de Chelly National Monument, and on the east by the Chuska Mountains. The two plots are from the Navajo Forestry Department Continuous Forest Inventory, plots 942 and 1833. The two plots have similar characteristics in elevation, slope aspect, and slope grade (Table 1). They were selected from a broader sample of CFI plots to assess climatic sensitivities of tree growth across PIPO-dominated forests of the Navajo Nation (Guiterman 2016) because they were only two plots that included all three targeted conifer species.

The average climate of the study area consists of bimodal precipitation, with much of the precipitation as rain during the summer monsoon season, July-August, and the rest as cool-season precipitation, October-March. Summer months are hot and dry, leading to high atmospheric evaporative demand. Average monthly precipitation (PPT) and vapor pressure deficit (VPD) for the region are shown in Figure 2.

### **2.2 Sample Collection and Processing**

At both CFI plots, two increment core samples were taken at 10-20 cm above ground from at least 5 trees of each species. Tree sampling was non-selective, and included

the largest trees across the plots to ensure the longest tree-ring chronologies. The increment cores were packaged in paper straws for further processing at the Laboratory of Tree-Ring Research (LTRR), University of Arizona, in Tucson, Arizona.

Increment cores were glued to wooden core mounts with cells oriented vertically, and tied with string. After drying, the string was removed and the top surfaces of the cores were sanded using a belt sander, starting with 220-grit sandpaper and using progressively finer grits, ending with 400-grit sandpaper. The cores were then sanded by hand with 30-micron and 15-micron sandpaper, followed with jewelry polishing paper until surfaces were smooth, and individual wood cells were visible under a high-powered light microscope.

### **2.3 Crossdating and Measuring**

Cores were visually crossdated using a microscope, using standard crossdating methods (Douglass, 1941): by skeleton-plotting and matching patterns of relative narrow and wide tree rings across all trees from the same site and assigning a calendar year to each growth ring. For each core, ring widths were measured to the nearest micrometer on a Velmex Tree Ring Measuring System (Velmex.com) and a microscope with a crosshair. Measurements were recorded using Tellervo, a desktop application for measuring and curating dendrochronological samples, written by Peter Brewer (LTRR) and is available free of cost at [tellervo.org](http://tellervo.org).

### **2.4 Quality Assurance**

Ring width measurement series were checked for dating and measurement errors using the computer program COFECHA, written by Richard L. Holmes in 1982.

COFECHA uses the following process. The biological growth trend is first removed by applying a 32-year cubic smoothing spline. Then auto-regressive (AR) modeling is applied, and AR processes are removed. This results in only one possibility for a dating match. The remaining pre-whitened data series is then log-transformed to give proportional ring width differences more equal weight, and each series is divided into 50-year segments. The segments of one series are then correlated with the mean of all the other series at the dated position and at positions lagged  $\pm 10$  years. Segments on each series with a higher correlation at a position other than the dated position are flagged for review (Grissino-Mayer, 2001). Series with flagged segments were then re-evaluated as needed under the microscope and dating errors were resolved.

## **2.5 Data**

### ***Species Chronologies***

To make chronologies for each species, first the age-growth trend was removed from each raw ring width series with a 100-year cubic smoothing spline (Cook and Peters, 1981). The resulting unit-less index series were then AR modeled, and autocorrelative processes were removed, resulting in residual series. Average value chronologies were built from the residual series, using the bi-weight robust mean (Mosteller and Tukey, 1977). Here it should be noted that chronologies initially were built by site and by species, but the similarity between the two sites allowed for the trees of the same species from both sites to be pooled together, and just one pooled chronology for each species was used in the analysis. All calculations pertaining to detrending, AR modeling, and building mean value chronologies were done in the RStudio environment, using the dplR package (Bunn, 2008).

## ***Climate Data***

Monthly climate data were obtained from the Precipitation-Elevation Regression on Independent Slopes Model (PRISM; Daly et al. 2008). The gridded climate time series included precipitation (PPT), maximum temperature, minimum temperature, and dewpoint from 81 4-km grid cells averaged across the study area ( $3^{\circ} \times 3^{\circ}$ ). I obtained vapor pressure deficit (VPD) as calculated following standard methods based on the temperature and dewpoint data (A.P. Williams, Lamont-Doherty Earth Observatory, *personal communication*).

## **2.6 Analysis**

### ***Climate Response***

Species were evaluated for differential climate response by comparing the three chronologies; chronologies that crossdate well are responding similarly to climate. I identified three major drought periods occurring within the instrumental data period based on periods of restricted growth in the chronologies. To evaluate whether species were responding to climate in the same seasons, correlation between chronologies and monthly PPT and VPD was performed in Matlab using the program SEASCORR (Meko, *et al.*, 2011). I identified the important seasons for each climate variable based on the output from SEASCORR, and used those seasons in further analysis.

### ***Tree Productivity***

Growth or relative productivity among the three species was analyzed by calculating the median basal area increment (BAI) of each species as a time series. BAI

is a measure of the cross-sectional area added to a tree in each year's growth. BAI was also compared across the three species for each drought period.

### ***Change in Climate Signal***

To evaluate the temporal stability of the response to climate, a sliding correlation was performed on the chronologies and two climate time series, PPT and VPD, which were built using the seasons determined to be important in earlier analysis. Regression analysis was performed on the chronologies, with the ring width index (RWI) as a function of PPT. These analyses were all performed in Matlab.

## **3. RESULTS**

From the two Navajo CFI plots, we pooled together series of the same species, and created three new chronologies with a total of 42 trees (84 cores), that together span over four centuries (Figure 3). The PIED chronology consists of 18 trees and spans 1753-2014. The PIPO chronology consists of 9 trees and spans 1684-2014. The PSME chronology consists of 15 trees and spans 1612-2014. Statistics for the chronologies are shown in Table 2, which emphasize high growth coherence and strong climate signals. Based on the ring width index chronologies, I identified three drought periods for further evaluation (1896-1904, 1950-1959, and 2000-2006).

Correlation of the chronologies with monthly climate data revealed October-May PPT and April-June VPD to be important seasonal signals in all three species (Figures 4-6). There were no obvious differences among species. In a simple correlation, Oct-May PPT correlated positively with PIED, PIPO, and PSME RWI, with correlation

coefficients of 0.72, 0.74, and 0.79 respectively. In a partial correlation, Apr-Jun VPD correlated negatively with PIED, PIPO, and PSME RWI with partial correlation coefficients of -0.48, -0.47, and -0.47 respectively. Comparing the three species across three different droughts showed no differences in RWI for different droughts, and no differences among species (Figure 7).

Analysis of BAI showed that PIPO and PSME were similar in productivity, and both were more productive than PIED. PIPO and PSME showed more variability in productivity through time. All three species showed a decline in growth during drought periods (Figure 8). Comparing BAI between droughts and species showed a slight increase in BAI for PIED and PSME, and a slight decrease in BAI in PIPO (Figure 9).

The correlation between RWI and the two seasonal climate factors are temporally stable, with strong positive correlation with PPT, and strong negative correlation with VPD throughout the century. Correlation with VPD becomes slightly stronger in the last couple of decades (Figures 10, 11). Residuals from regression analysis on the chronologies, using seasonal PPT to predict RWI, resulted in a random normal scatter when plotted against PPT (Figure 12), and a very slight negative trend when plotted against VPD (Figure 13).

## 4. DISCUSSION

### ***Climate Response***

*Are the three species at these sites responding differently to climate?*

Based on this study, there is no evidence for species-level differences in response to climate, when other factors such as elevation, slope, soil conditions, and so forth, are controlled. This is shown in the high interspecies correlation of the PIED, PIPO, and PSME chronologies, there are no species differences in climate response. This result is underscored by seasonal correlations (Figures X-X); all three species are responding to similar seasons, and all with very similar strength in correlation. In addition, there is no difference between species in terms of their climate response during drought periods.

### ***Tree Productivity***

*Are there differences in tree productivity between the species at these sites, and specifically, does Douglas-fir show some signs of stress?*

Our BAI analysis does indicate that there are differences in tree productivity among species, namely that PIED is less productive than either PIPO or PSME. This is likely due to life history traits of PIED, which is a slow-growing tree. It is generally considered a woodland species that lives in an open canopy. At these sites, it is growing under the much higher canopy of PIPO and PSME, and thus is likely experiencing some competition for sunlight and other resources. Contrary to our prediction, PSME shows no sign of stress in terms of its productivity; it has been growing at a rate similar to PIPO throughout the period of analysis. Though this result must be tested in similar situations across many more sites, this could have important implications for the health of PSME

at higher elevation sites as temperatures continue to rise. Another result from this analysis is that, even though there are differences overall in species productivity, growth is reduced to near zero levels across all species in severe drought years, synchronizing all the species. This effect is temporary, and when wetter conditions return, tree growth returns to normal.

### ***Change in Climate Signal***

*How has recent upward trending temperature-driven atmospheric moisture affected these three species?*

The climate signal in all three species is very stable through time, evidenced by the strong and consistent running correlation analysis (Figure X). Based on the residuals from the regression analysis (Refer to Figure 12), PPT remains a main driver of tree growth, but in the past couple of decades, there is a hint that VPD may be playing a larger role in reducing tree growth, as shown in the stronger negative correlation to VPD in recent years (Figure 11). In addition, residuals from the regression analysis plotted as a function of VPD show a slight negative trend (Figure 12). This suggests that in years when PPT does not predict tree growth as well, VPD may be playing more of a role in limiting tree growth, and the difference in what PPT cannot predict may be explained by high VPD. Although the trend is not statistically significant, this may be an additional hint that in years with high VPD, a given amount of precipitation does not count for as much

### ***Implications***

We found that in our two mid-elevation Southwest forest sites, piñon, ponderosa, and Douglas-fir are responding to climate very similarly. Their growth is driven mostly by

cool season precipitation, with pre-monsoon VPD limiting growth. These broad similarities in climate response contrast with the idea that forest resilience to future droughts will be species dependent. Our findings, therefore, indicate that drought effects could be seen across sites such as ours with growth declines, and potentially mortality events, occurring synchronously and cross-species. However, we found that all trees are highly responsive to drought events, with growth recoveries occurring within a year or two after near-zero ring growth. Should average climate conditions trend toward those of the worst droughts in our record – as they are projected to – these trees may experience longer-term growth declines as they did during extreme single-drought years such as 2002.

The presence of PSME growing at this mid-elevation site, and our observation of its production rates being similar to PIPO, may be encouragement that as climate continues to warm, PSME may not be at higher risk than PIPO or PIED.

Lastly, the hint at VPD becoming an increasingly important driver in restricting growth may be indicative of a future decoupling of tree growth with PPT. Because of the slightness in the trend and the poor fit of our model (Figure 13), we cannot place great confidence in this conclusion. It certainly warrants further testing across more sites and at broader spatial scales. All of the residuals at high VPD fall short in terms of growth predicted by PPT alone. Recent VPD trends have risen above average and not returned to historic values (Figure 14). Given these two pieces of evidence, and that future climate will include rising temperature and VPD at unprecedented levels, we might yet see a strengthening in this trend of VPD becoming more of a driver in growth restriction.

## 5. CONCLUSIONS & FURTHER WORK

Higher temperatures are expected of future climate, and although predictions of precipitation are less certain, drought will occur more often based solely on the relationship between temperature and increased atmospheric evaporative demand (Weiss, *et al.*, 2009). This generally means greater drought stress on forests, leading to higher tree mortality, often causing changes in ecosystem composition and/or structure. The synchrony that we found across species to climate means that at these sites, all species have a roughly equal chance of survival. The hint of VPD strengthening its control on limiting growth may mean that in a future with hotter climate and higher VPD, more precipitation will be required to sustain present-day tree growth and productivity, which is not a feature of climate that can be depended on with present knowledge. This study was limited to a small number of sites, so this finding is not conclusive, but it warrants further study, including more sites, and possibly controls on age and structure of the population.

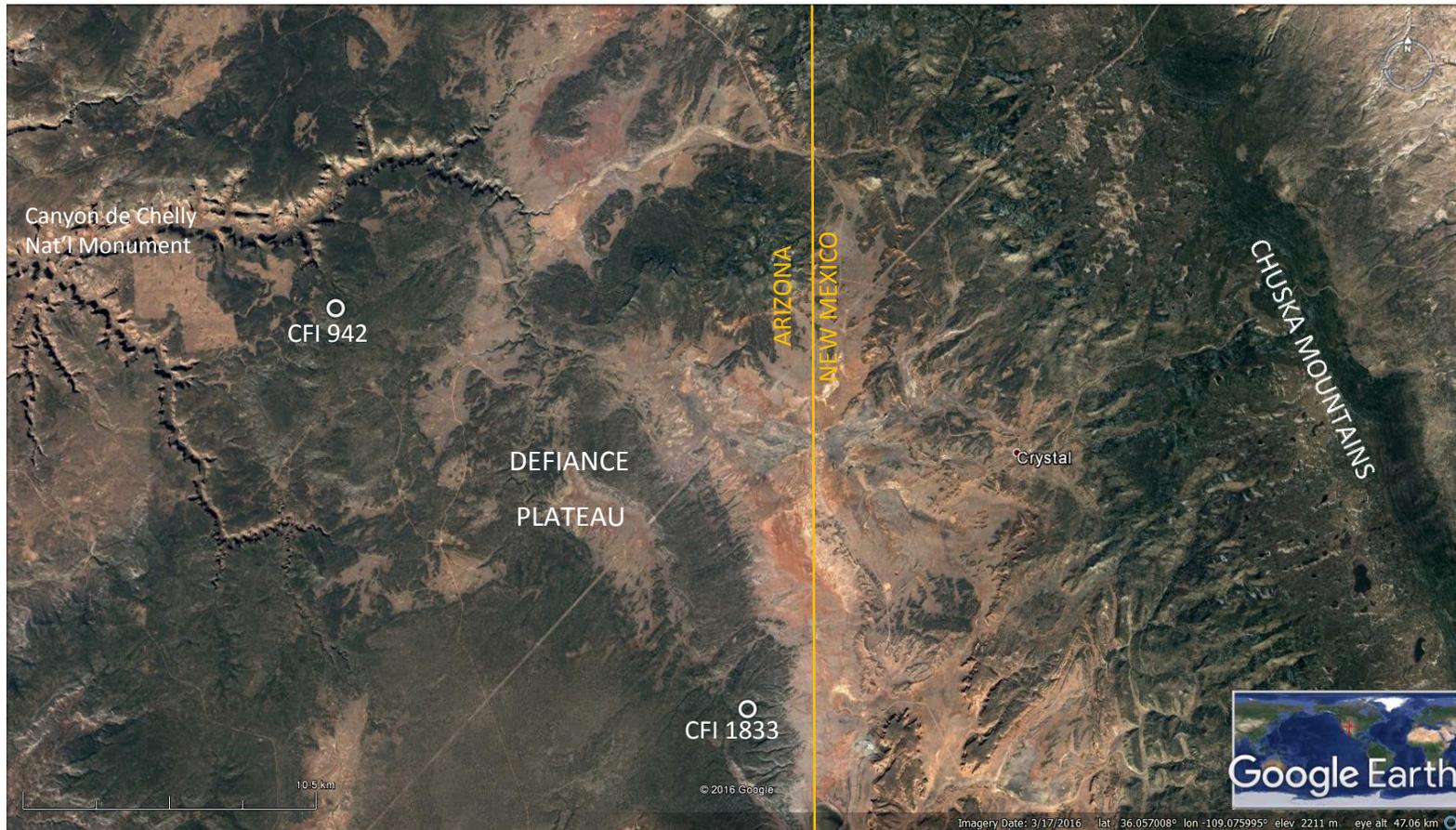
## References

- Abatzoglou, J.T., A.P. Williams, (2016), The impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, *In press*.
- Allen, C.D. et al. (2010), A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*, 660–684.
- Allen, C.D., D.D. Breshears, N.G. McDowell (2015), On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*, art.129
- Bunn, A.G. (2008), A dendrochronology program library in R (dplR). *Dendrochronologia*, *26*, 115–124.
- Cook, E.R., K. Peters (1981), The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin*, *41*, 45-53.
- Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. Pasteris, (2008), Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology* *28*, 2031–2064.
- Douglass, A.E. (1941), Crossdating in dendrochronology. *Journal of Forestry*, *39*, 825-831.

- Grissino-Mayer, H.D. (2001), Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Research*, 57, 205-221.
- Guiterman, C.H. (2016), Climate and human drivers of forest vulnerabilities in the US Southwest: Perspectives from dendroecology. Doctoral thesis, University of Arizona, School of Natural Resources and the Environment. 185 p.
- Meko, D.M., R. Touchan, K.J. Anchukaitis, (2011), Seacorr: A MATLAB program for identifying the seasonal climate signal in an annual tree-ring time series. *Computers and Geosciences*, 37 1234–1241.
- Mosteller, F., J.W. Tukey, (1977), Data Analysis and Regression: a second course in statistics. *Addison-Wesley*. ISBN-13: 978-0-201-04854-4.
- Weiss, J.L., C.L. Castro, J.T. Overpeck, (2009), Distinguishing pronounced droughts in the southwestern United States: Seasonality and effects of warmer temperatures. *Journal of Climate*, 22, 5918–5932.
- Williams, A.P., C.D. Allen, C.I. Millar, T.W. Swetnam, J. Michaelsen, C.J. Still, S.W. Leavitt, (2010), Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 21289–21294.
- Williams, A.P. et al., (2012), Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, 3, 292–297.

Woodhouse, C.A., G.T. Pederson, K. Morino, S.A. McAfee, G.J. McCabe, (2016),  
Increasing influence of air temperature on upper Colorado River streamflow.  
*Geophysical Research Letters*, 43, 2174-2181.

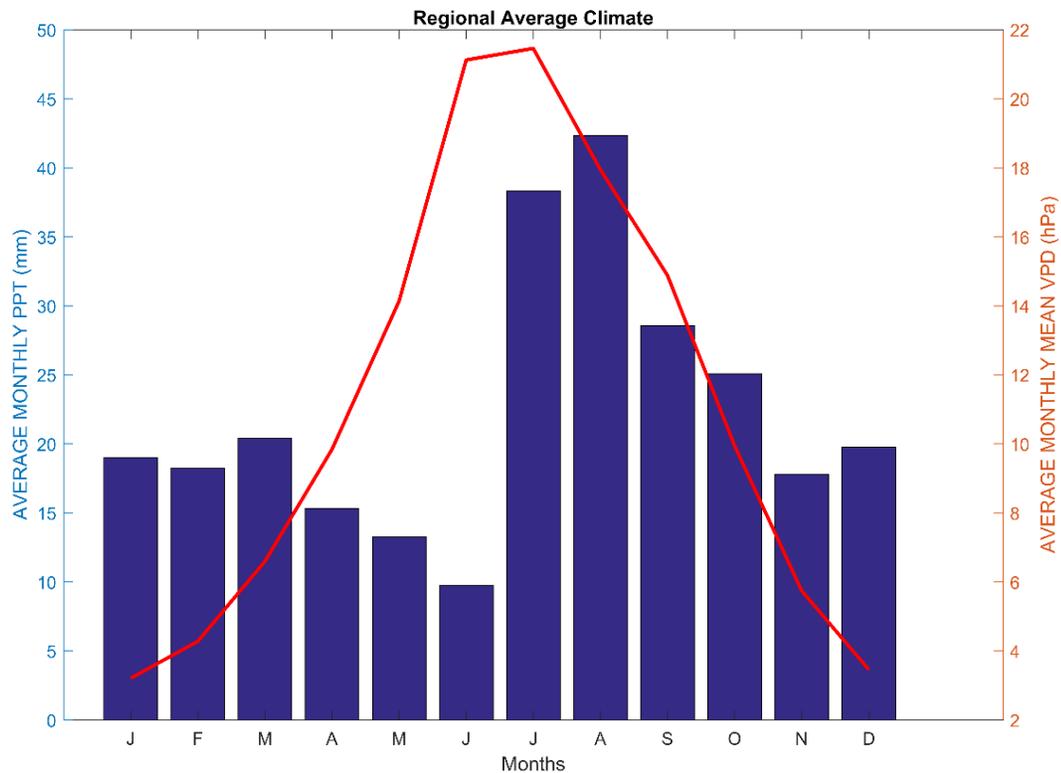
## Figures



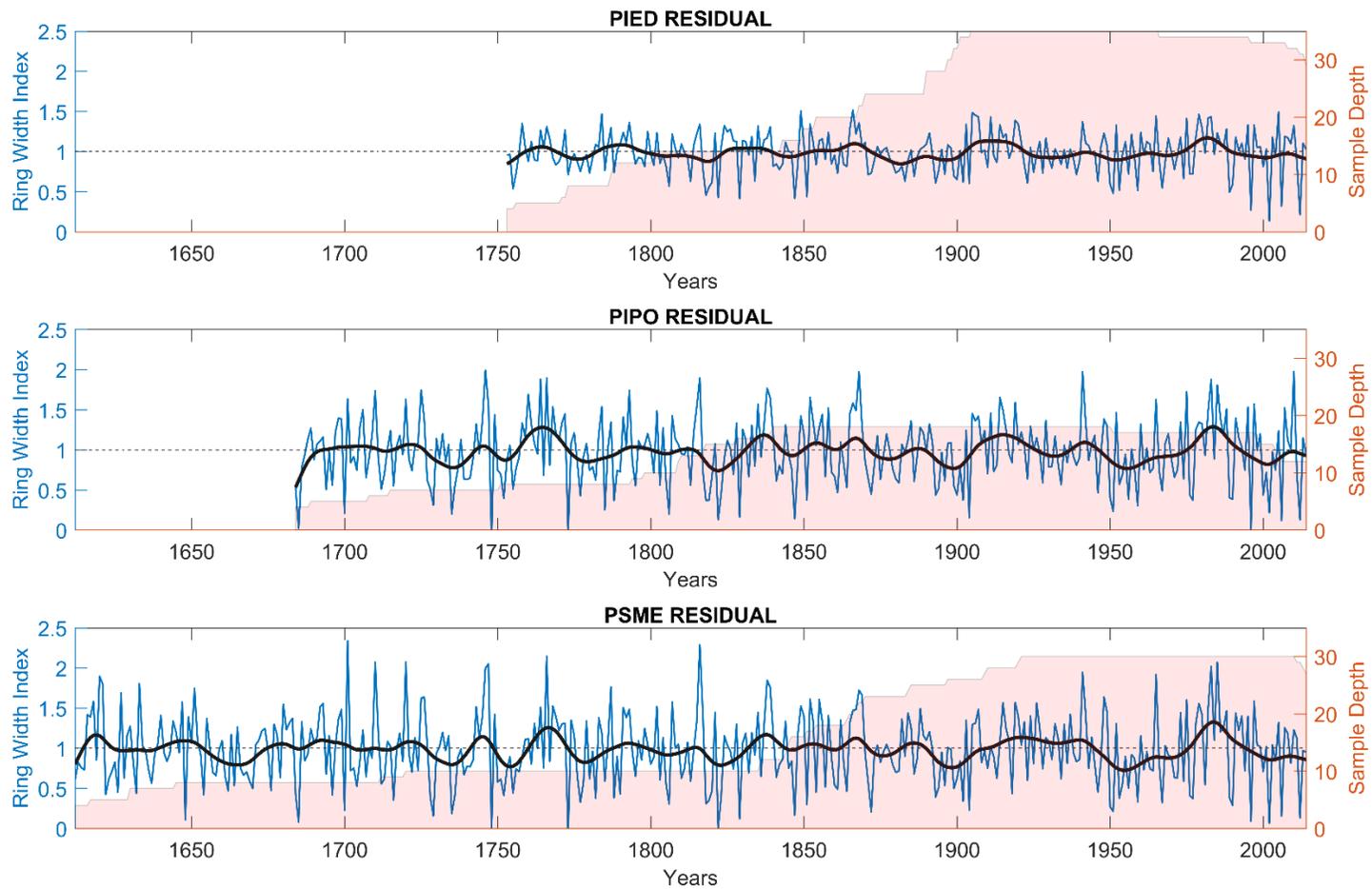
**Figure 1.** Location of research area: Navajo CFI plot 942 (36.092139 °N, -109.233667 °E, 2321 m elev.) and plot 1833 (35.964861 °N, -109.072222 °E, 2305 m elev.) on the Defiance Plateau in northeastern Arizona.

**Table 1.** Site details for Navajo CFI plots 742 and 1833. The two sites are both on the Defiance Plateau. They have similar north-facing aspects, slopes, and elevation.

<b>Plot ID</b>	<b>Lat, deg</b>	<b>Lon, deg</b>	<b>Elev, m</b>	<b>Aspect, deg</b>	<b>Slope %</b>
942	36.092139	-109.233667	2321	330.7	14
1833	35.964861	-109.072222	2305	67.7	15



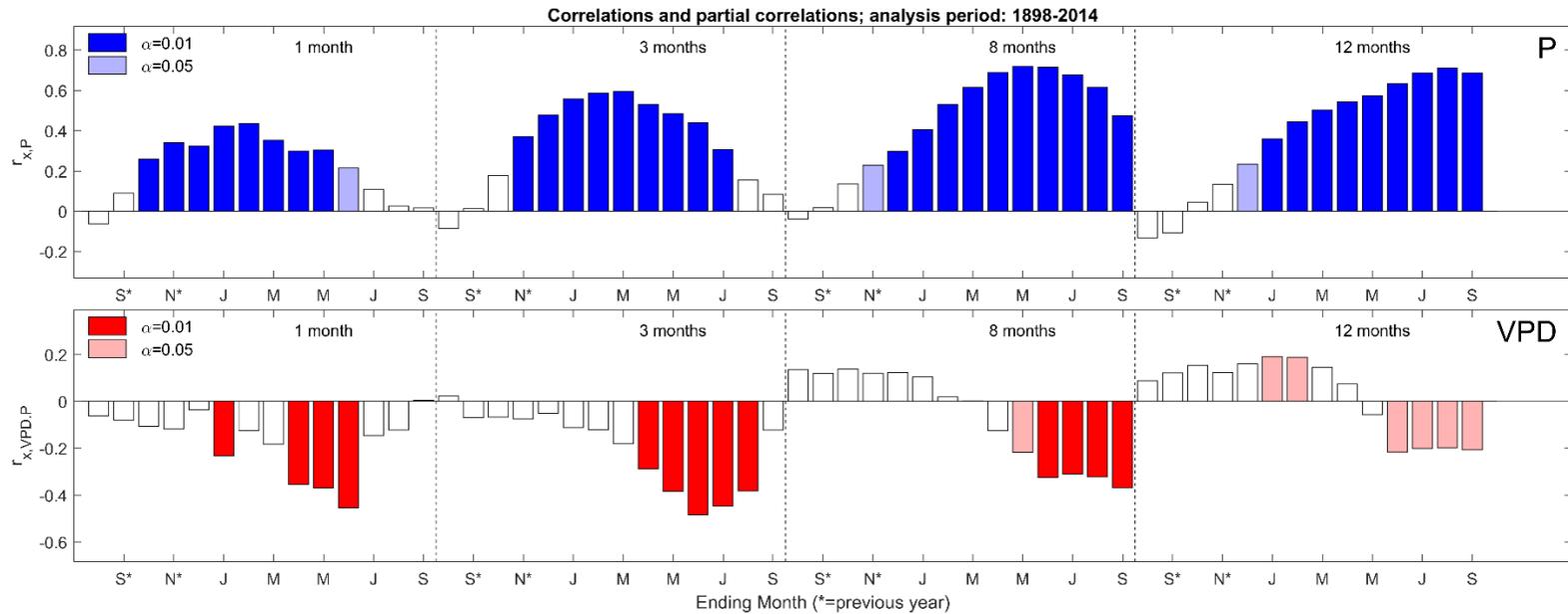
**Figure 2.** Average monthly total precipitation (PPT) and average monthly mean vapor pressure deficit (VPD) for the Southwest, averaged across 1895-2014. Climate data originates from gridded monthly climate data from The PRISM Climate Group, Oregon State University. Regional averages for Southwest provided to us by A. Park Williams, VPD calculated by Williams from PRISM dataset.



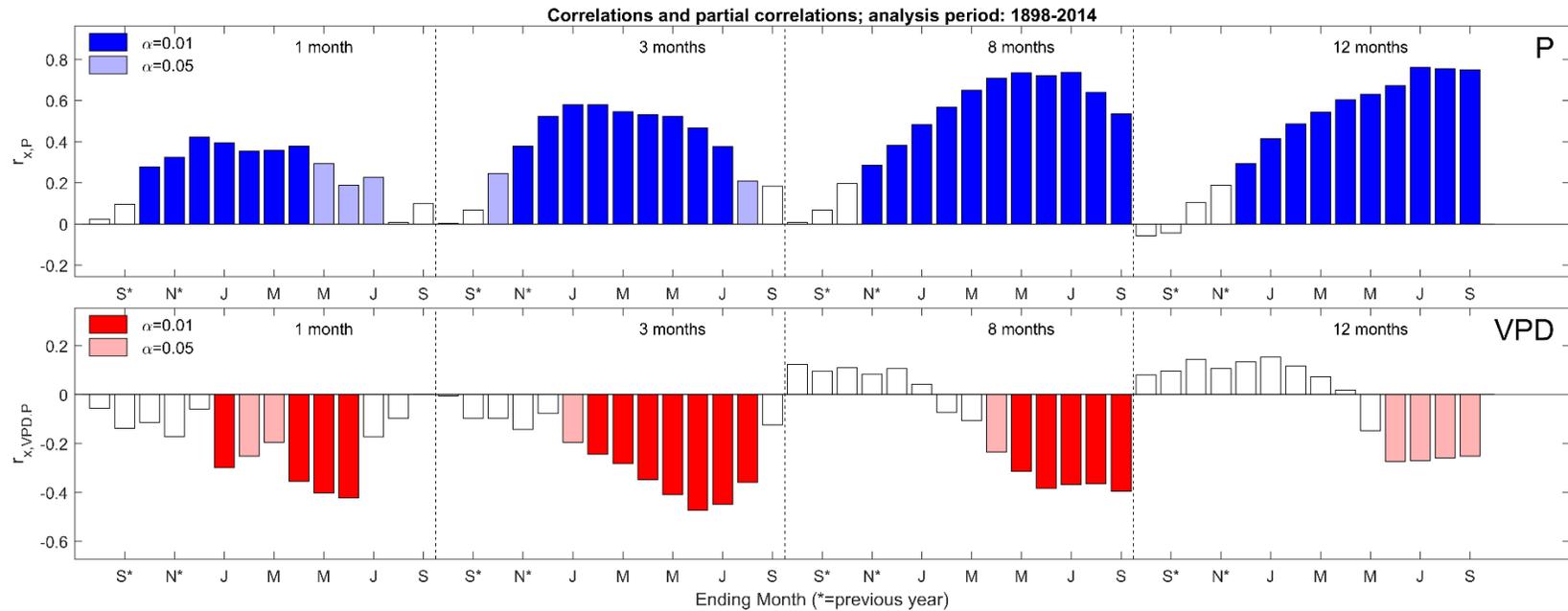
**Figure 3.** Residual chronologies, by species, for the two pooled CFI plots, 942 and 1833. The blue line shows the residual chronology, with a 20-year spline overlaid in black to illustrate the overall trend. Sample depth is shown in the background in light red. Chronologies were cut off where sample depth was less than 4 cores. Prominent periods of below-average growth during the instrumental period include the 1890s-1900s, 1950s, and 2000s, which correspond to three known droughts in the Southwest region.

**Table 2.** Statistics for residual species chronologies.

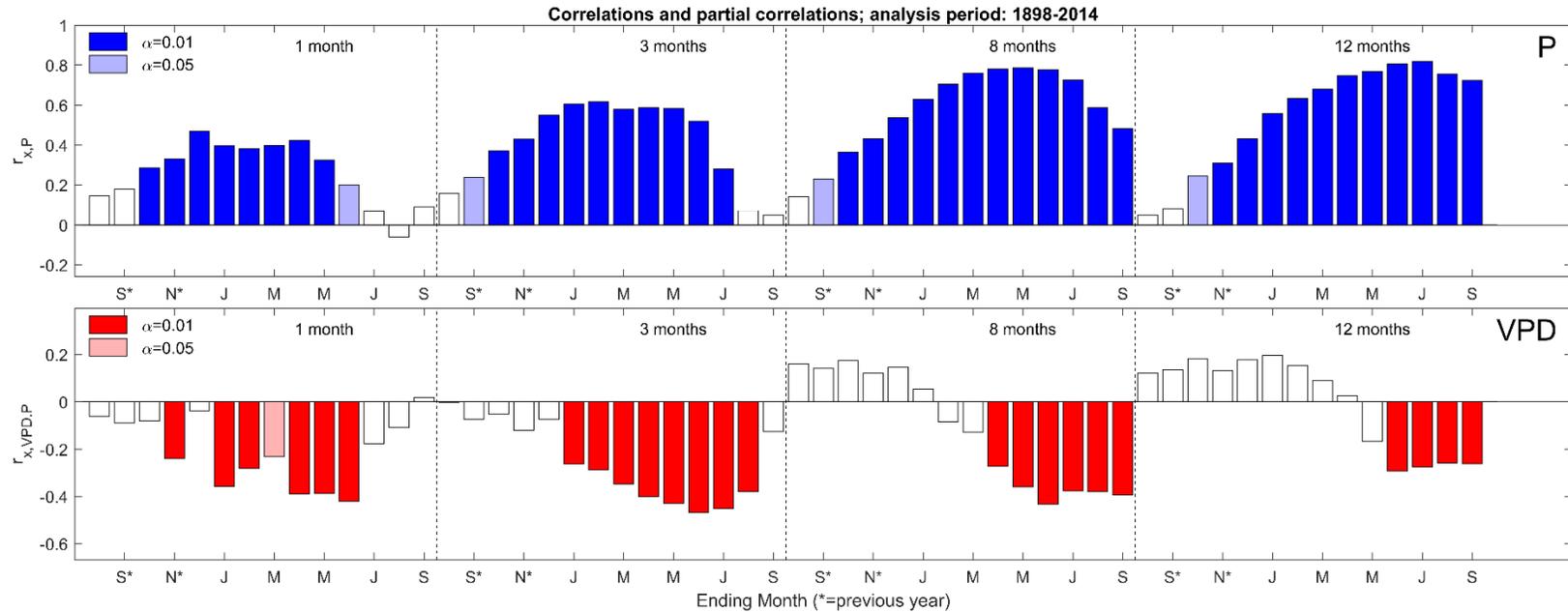
<b>species</b>	<b>first.yr</b>	<b>last.yr</b>	<b>n.cores</b>	<b>n.trees</b>	<b>n</b>	<b>n.tot</b>	<b>n.bt</b>	<b>rbar.tot</b>	<b>rbar.wt</b>	<b>rbar.bt</b>	<b>c.eff</b>	<b>rbar.eff</b>	<b>mean</b>	<b>stdev</b>	<b>eps</b>	<b>snr</b>
<b>PIED</b>	1753	2014	36	18	6.767	630	612	0.512	0.73	0.505	2	0.584	0.983	0.257	0.905	9.501
<b>PIPO</b>	1684	2014	18	9	4.974	153	144	0.701	0.873	0.69	2	0.737	0.98	0.411	0.933	13.926
<b>PSME</b>	1612	2014	30	15	7.407	435	420	0.709	0.872	0.703	2	0.751	0.984	0.436	0.957	22.38



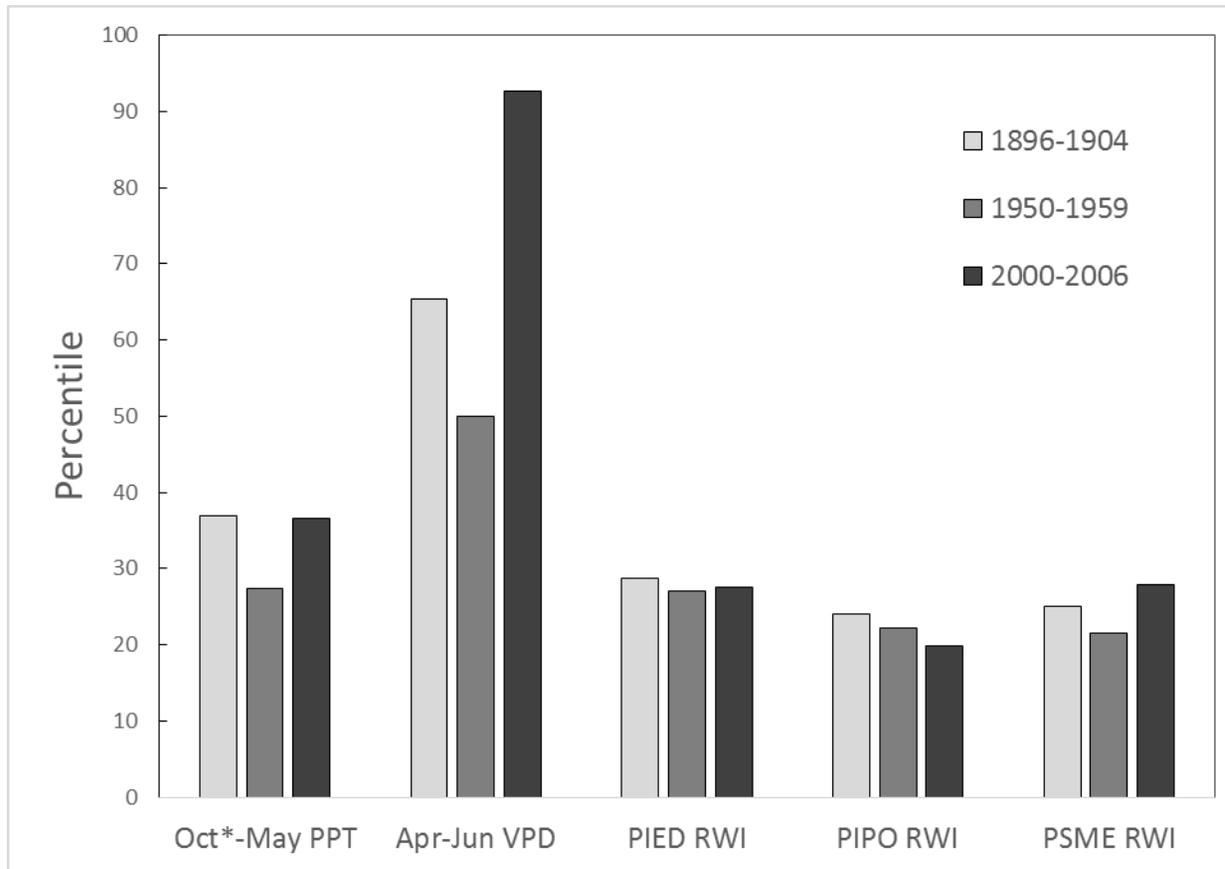
**Figure 4.** PIED RWI simple and partial correlations with seasonal climate variables, PPT and VPD. Many seasonal groupings of monthly data correlated strongly with the chronology at the alpha = 0.01 significance level. For PPT, the season including cool season and pre-summer, October-May, was a dominant signal in the PIED RWI, with correlation coefficient  $r = 0.72$ . For VPD, the dominant signal was the season including the hot summer months April-June, with a partial correlation coefficient  $r = -0.48$ .



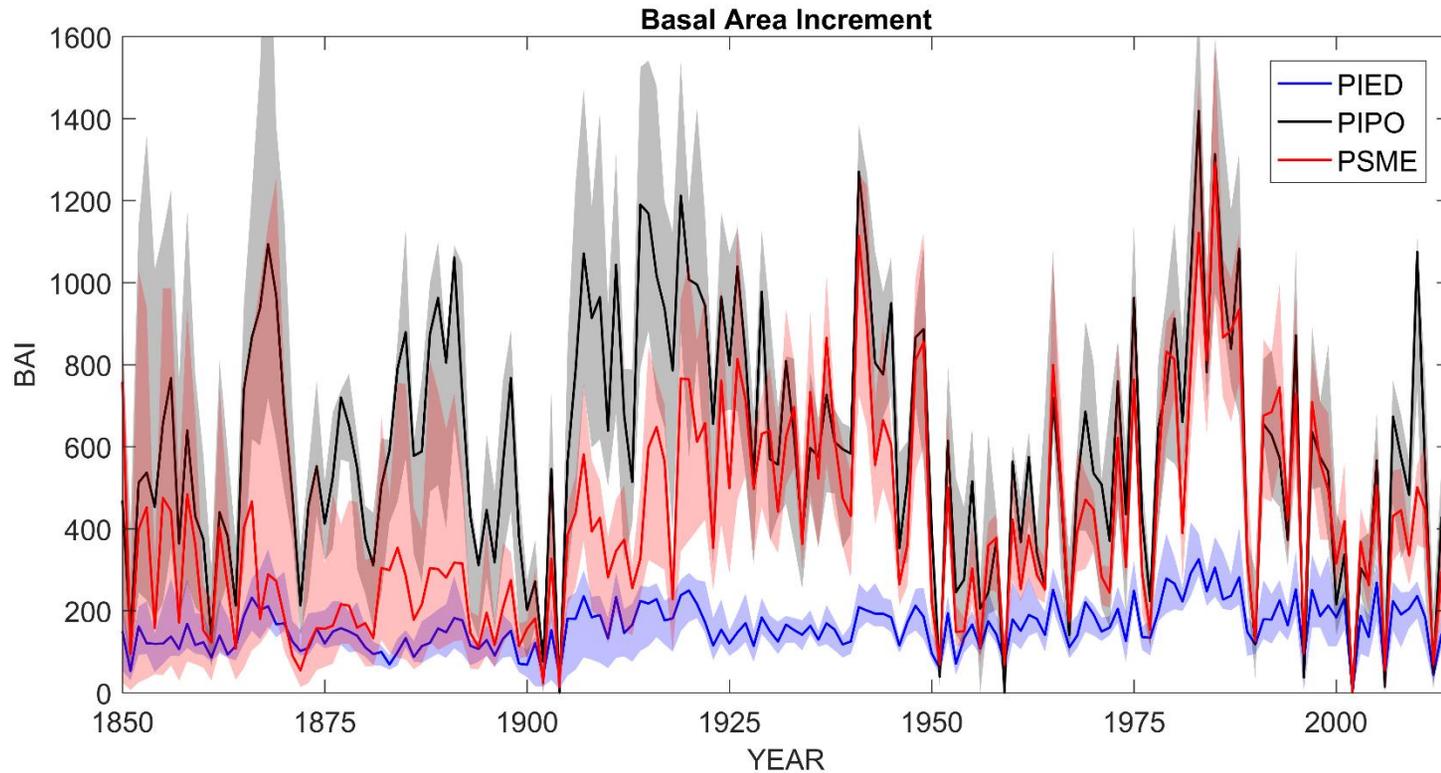
**Figure 5.** As in previous figure, but for PIPO. Again, many seasonal groupings of monthly data correlated strongly. For PPT, cool season to pre-summer, October-May, was a dominant signal in the PIPO RWI, with correlation coefficient  $r = 0.74$ . For VPD, the dominant signal was the season including the hot summer months April-June, with a partial correlation coefficient  $r = -0.47$ .



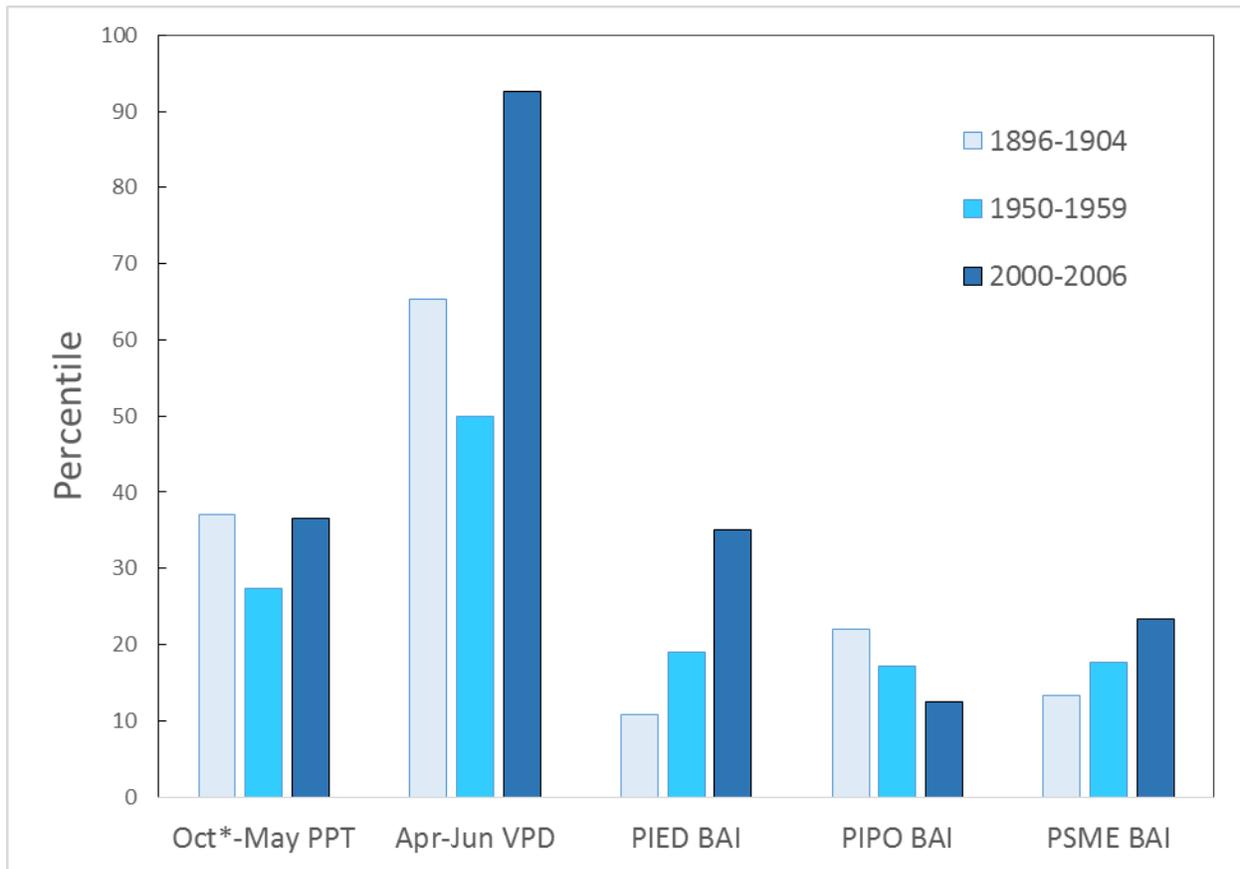
**Figure 6.** As in previous figure, but for PSME. For PPT, cool season to pre-summer, October-May, was a dominant signal in the PSME RWI, with correlation coefficient  $r = 0.79$ . For VPD, the dominant signal was the season including the hot summer months April-June, with a partial correlation coefficient  $r = -0.47$ .



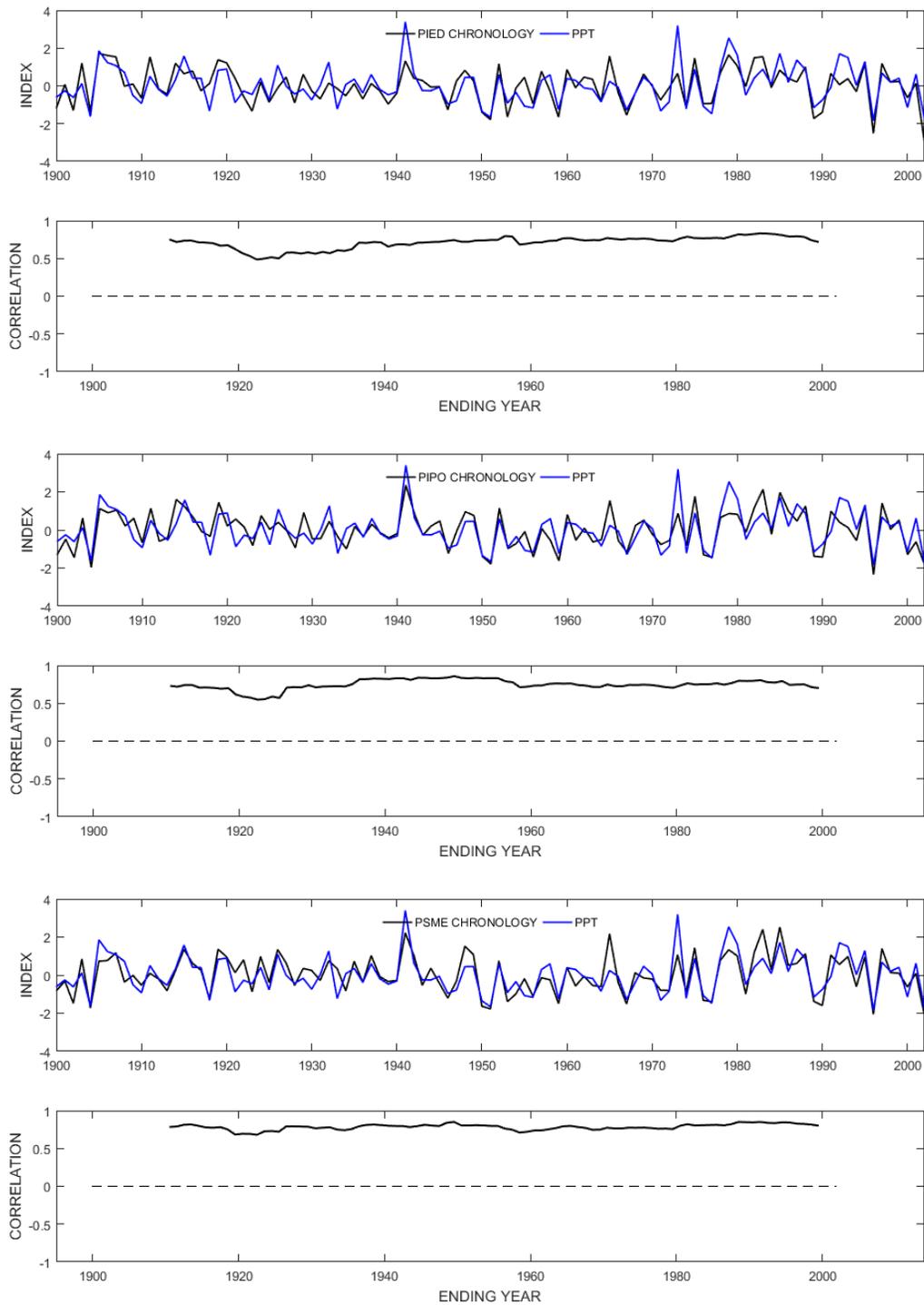
**Figure 7.** Comparison of seasonal PPT, VPD, and RWI for each species, during three separate drought periods: 1896-1904, 1950-1959, 2000-2006. Asterisk (\*) after a month signifies it is from the year previous to the growing year. Values reported means for the drought period, and calculated percentile ranks out of the entire 1896-2014 period. In terms of climate, the 2000s drought was wetter than the 1950s drought, but had a much higher VPD, which leads to a greater evapotranspiration demand on trees. The RWI for all species is low for each of the droughts, and there is no marked difference in RWI between drought periods. This analysis was adapted from (Woodhouse, *et al.*, 2016).



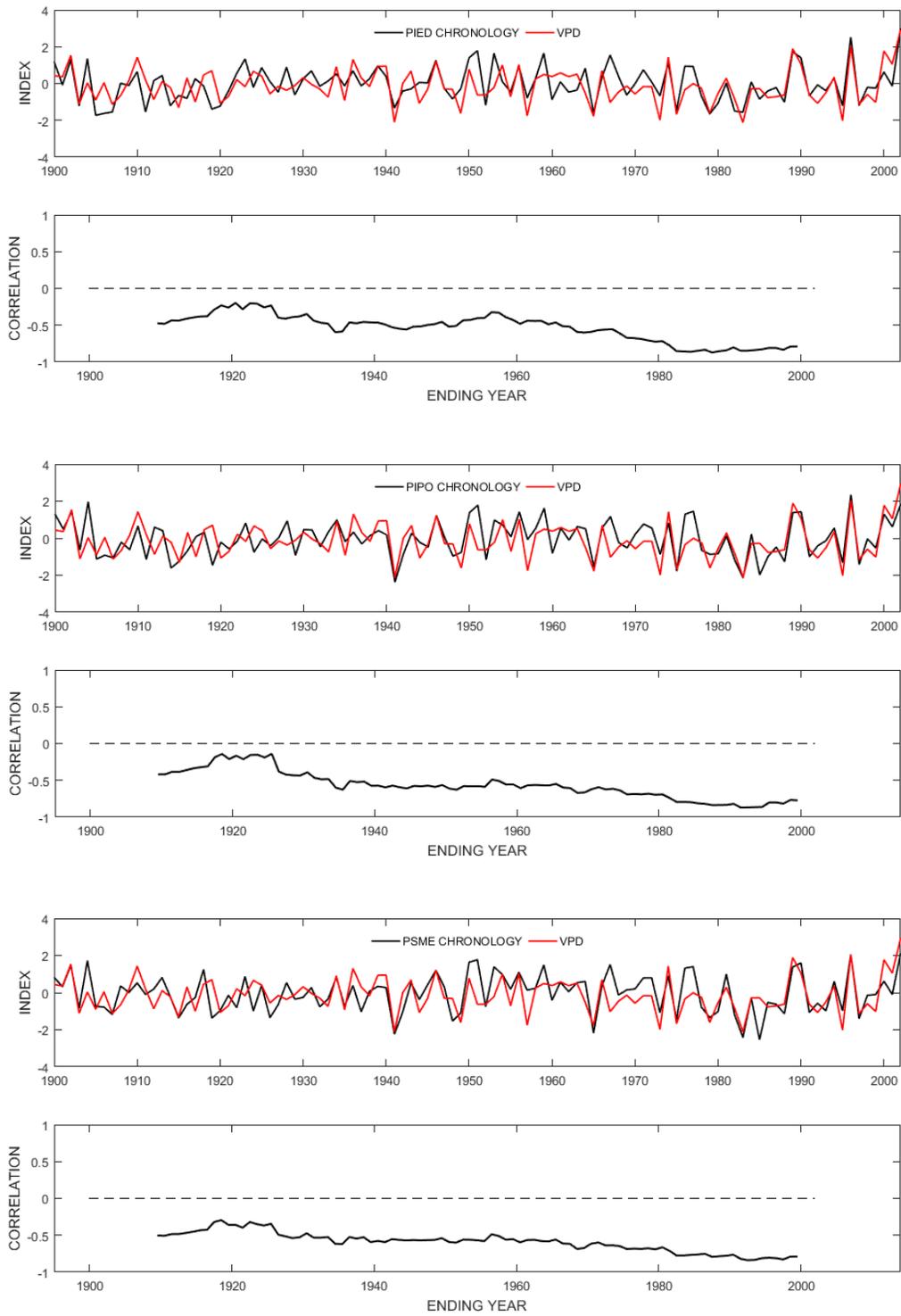
**Figure 8.** Basal Area Increment (BAI) for each of the three species, calculated for the period 1850-2014. Solid lines are the median BAI, and shaded regions represent the inter-quartile range. Preliminary analysis shows that overall, PIPO and PSME have more inter-annual variability in productivity than PIED, and all have reduced growth in droughts of 1950s and 2000s. There seems to be a steady increase in PIED productivity, though further analysis is needed to determine statistical significance of this trend.



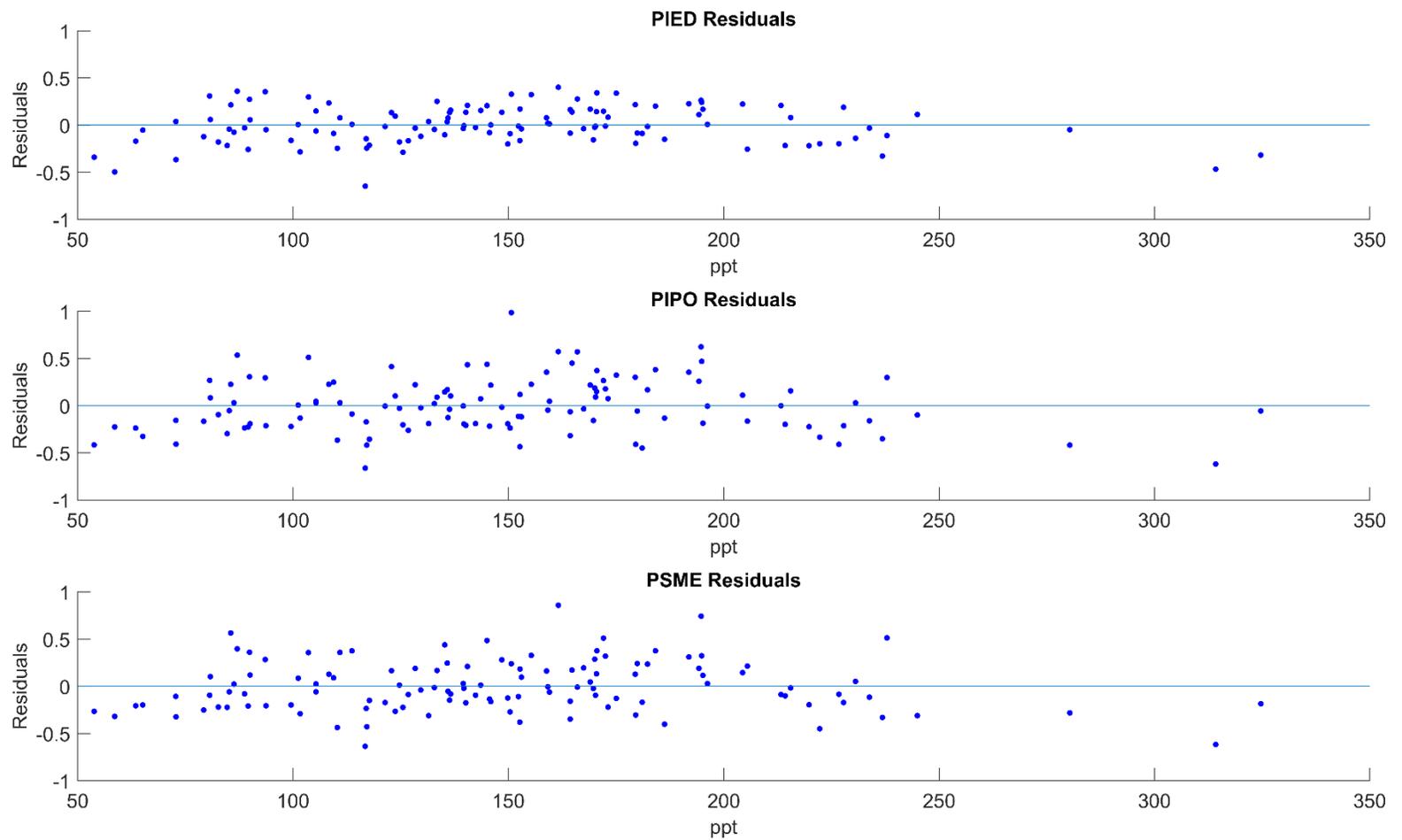
**Figure 9.** Comparison of seasonal PPT, VPD, and BAI for each species, during three separate drought periods: 1896-1904, 1950-1959, 2000-2006. Asterisk (\*) after a month signifies it is from the year previous to the growing year. Values reported means for the drought period, and calculated percentile ranks out of the entire 1896-2014 period. There is a slight increase in BAI for PIED from the 1950s drought to the 2000s drought, but no other striking differences in BAI across droughts or between species for each drought. Analysis adapted from (Woodhouse, *et al.*, 2016).



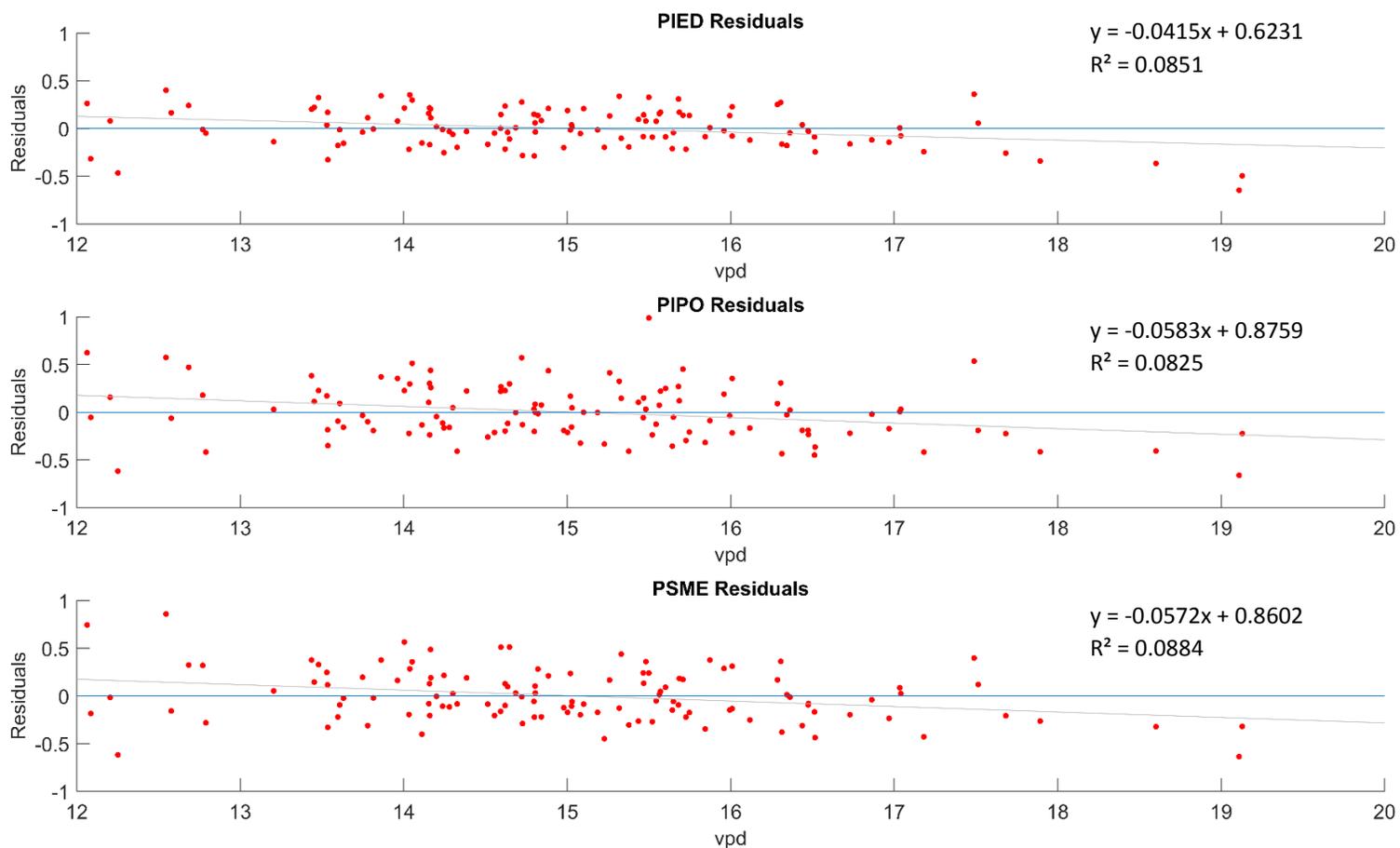
**Figure 10.** Simple correlation between October-May PPT and the three species, PIED, PIPO, PSME ring width indices is strong and temporally stable throughout the 20<sup>th</sup> century and into the early 21<sup>st</sup> century. Sliding correlation calculated with a 30-year window.



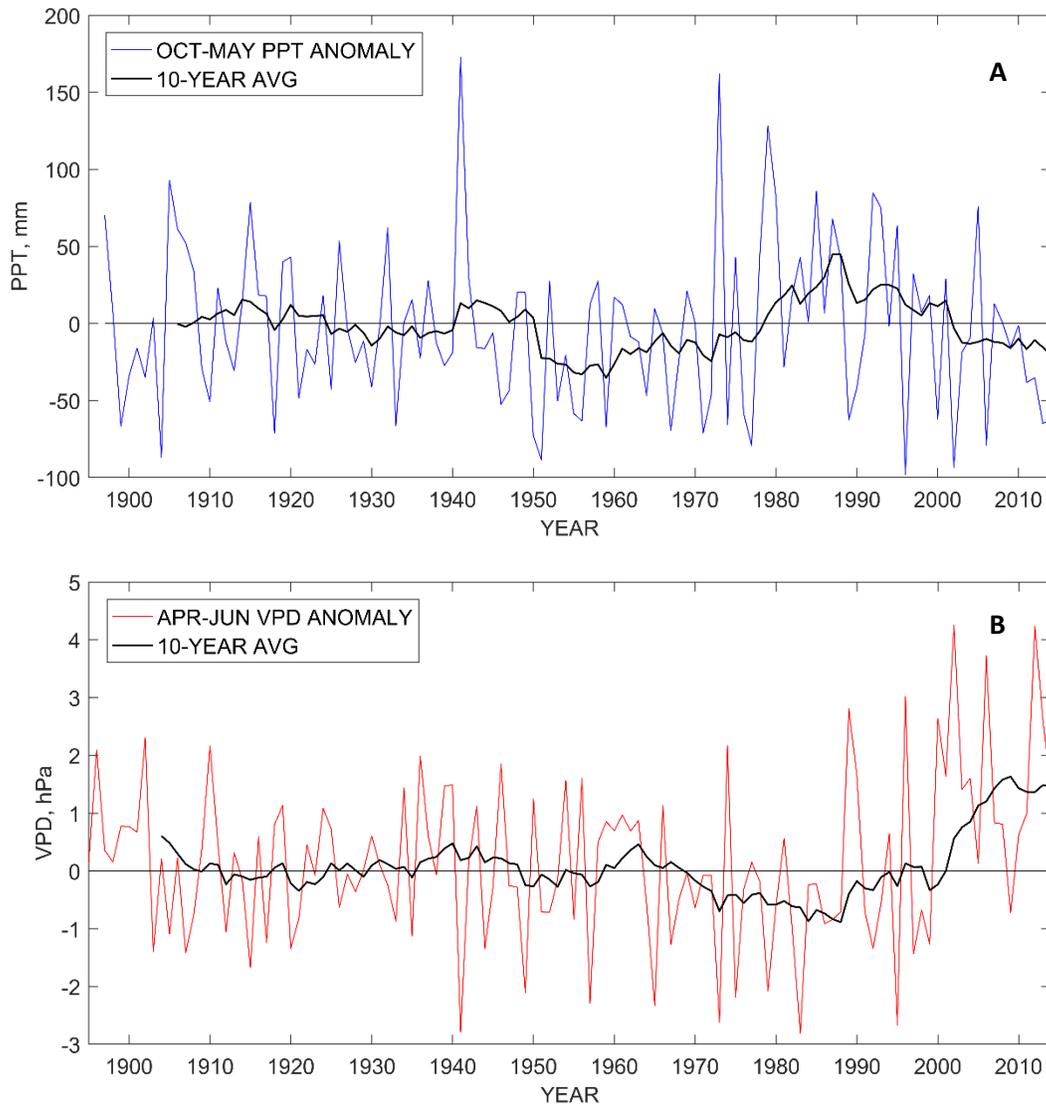
**Figure 11.** Partial correlation of April-June VPD with the PIED, PIPO, and PSME ring width indices is mostly stable throughout, but becomes slightly stronger in the latter period. Sliding correlations calculated with a 30-year window.



**Figure 12.** Shown are residuals from linear regression of RWI as a function of Oct-May PPT, plotted against PPT. Also plotted is a least-squares line, overlapping almost entirely with the blue reference line. There is no trend to the least-squares line, indicating that PPT is a valid choice of variable for predicting RWI.



**Figure 13.** Shown are residuals from linear regression for all three species of RWI as a function of Oct-May PPT, plotted against VPD. Also plotted is a least-squares line, which shows a slight negative trend. Although the fit of the least-squares line is not high enough to interpret conclusively, there may be an indication that with increased VPD, VPD may play more of a role in decreased tree growth, and that PPT alone is not the only control on ring width.



**Figure 14.** Seasonal PPT and VPD reported as a 30-year anomaly, with respect to 1901-1930 period. Plotted in the black line is a 10-year running average. **A.** Oct-May PPT shows considerable variability through the instrumental period, and is decreased during 1950s and 2000s droughts. **B.** Apr-Jun VPD shows less variability for the majority of the first half of the century, but then shows an increase from 2000 onward, and not returning to historic values.