TREE-RING RESEARCH, *Vol. 75(1), 2019, pp. 25–33*
DOI: http://dx.doi.org/10.3959/1536-1098-75.1.25

CLIMATE-GROWTH RESPONSES FROM *PINUS PONDEROSA* TREES USING MULTIPLE MEASURES OF ANNUAL RADIAL GROWTH

PETER T. SOULÉ[1*], JUSTIN T. MAXWELL[2], and **PAUL A. KNAPP[3]**

[1]Appalachian Tree-Ring Laboratory, Department of Geography and Planning, Appalachian State University, Boone, NC, 28608, USA

[2]Environmental Tree-Ring Laboratory, Department of Geography, Indiana University, Bloomington, IN, 47405, USA

[3]Carolina Tree-Ring Science Laboratory, Department of Geography, University of North Carolina-Greensboro, Greensboro, NC, 27402, USA

ABSTRACT

When using old-growth trees from semiarid, open-canopy environments, basal area increment (BAI), an absolute measure of radial growth, is sometimes used instead of the more commonly used 'conservative techniques' (negative exponential or linear regression with a negative slope; NegX) because narrow rings have been shown to potentially bias results. In this study we explore the relationship between radial growth of ponderosa pine from four study sites in Montana and climate (temperature, precipitation, drought severity) using unstandardized raw ring width and BAI values, and standardized values generated via Friedman Super Smoother and NegX. All sites are minimally disturbed, and our selection criteria are limited to older (interior dates pre-A.D. 1850 at breast height) trees growing in open-canopy environments free of visible disturbance such as lightning strikes. We found the strongest relationships (r > 0.60) for radial growth with July and prior-year October Palmer Drought Severity Index values. Our results show that radial growth-climate responses generally fall within a narrow range regardless of the representation of annual growth (*e.g.* for July temperature r-values are largely –0.3 to –0.4) and that site conditions determine which radial-growth values (*i.e.* unstandardized or standardized) optimize climate-growth responses.

Keywords: tree rings, climate-growth responses, standardization techniques, ponderosa pine, Montana.

INTRODUCTION

For trees growing in semiarid, open-canopy environments, a common tree-ring standardization technique for maximizing climate response and/or for climate reconstruction is either negative exponential, linear regression of negative slope, or horizontal line (Cook 1985; Fritts 2012) (hereafter NegX and typically referred to as the 'conservative' option). In these open-canopy environments it is assumed that minimal influence on tree growth is caused by other trees (*e.g.* openings caused by windfall). Thus, NegX detrending removes the biological growth trend while preserving the climate signal (*e.g.* Villanueva and McPherson 1996; Grissino-Mayer and Swetnam 2000; Salzer and Kipfmueller 2005; Soulé and Knapp 2006; Knapp and Soulé 2011). When using old-growth trees from semiarid environments, basal area increment (BAI), an absolute measure of radial growth, is sometimes used (*e.g.* Biondi and Qeadan 2008; Knapp *et al.* 2013; Soulé and Knapp 2015; Castruita-Esparza *et al.* 2016). The narrow (<0.5 mm) growth rings that are commonly produced by trees in semiarid environments have been shown to potentially bias results when using a ratio-based approach for calculation of standardized indices (Cook and Peters 1997), and this problem can be avoided by using BAI. Further, a suite of standardization techniques are available to dendroclimatologists (*e.g.* double-detrending (Holmes *et al.* 1986), cubic splines (Fritts 2012), C-method, RCS (Biondi and Qeadan 2008)) and the benefits and limitations of various techniques have been extensively studied (*e.g.* Cook

*Corresponding author: soulept@appstate.edu

et al. 1995; Briffa *et al.* 1996; Cook and Peters 1997; Biondi and Qeadan 2008), often with a goal of illustrating where potential biases may result from the use of a given technique. This study is not a comprehensive examination of all available standardization techniques that can be applied; rather, our goal is to illustrate the utility of examining multiple techniques when determining the climate-growth response for samples collected from trees growing in semiarid, open-canopy forests.

In experimenting with ponderosa pine (*Pinus ponderosa* var. *ponderosa*; PIPO) chronologies developed to examine mountain pine beetle (*Dendroctonus ponderosae* Hopkins) responses (Knapp *et al*. 2013) and CO_2 enrichment (Soulé and Knapp 2015), we searched for a climate response from old-growth PIPO growing in western Montana and found no substantive differences in climate response between annual growth patterns via BAI and NegX. Here we explore the relationship between radial growth of PIPO and climate (temperature, precipitation, soil moisture) using absolute measures of radial growth (unstandardized radial growth values (hereafter RAW and BAI)), standardized radial growth values obtained through conservative techniques (NegX), and standardized values from a Friedman Super Smoother (Friedman 1984 (hereafter FRE)). FRE has been used successfully in both disturbed environments (*e.g.* Pederson *et al.* 2012; Devineni *et al.* 2013) and other semiarid, open-canopy environments (*e.g.* Allen *et al.* 2013; Bekker *et al.* 2014). The primary research questions addressed are: (1) Does the NegX standardization technique provide the strongest climate response for open-canopy PIPO growing in western Montana?; (2) What is the utility of using unstandardized measures of radial growth (*i.e.* RAW, BAI) for climate response?; (3) How does a more flexible standardization technique (*i.e.* FRE) perform for PIPO?; and (4) Are there significant differences in climate-growth relationships among the four techniques compared?

METHODS

We collected core samples from PIPO from four minimally disturbed, open-canopy woodland sites co-dominated by PIPO and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) in Montana (Table 1). Two of the sites (Ferry Landing [FLR: 47.329°N, 114.869°W] and Cabin Gulch [CGR: 46.856°N, 111.769°W]) are protected Research Natural Areas that were chosen because they represent "ecosystems in natural condition" (Evenden *et al.* 2001:1) where disturbance is minimal. Fish Creek (FCR: 46.856°N, 114.685°W) and Kitchen Gulch (KGR: 46.71°N, 113.659°W) represent areas where anthropogenic influences (*e.g.* logging) have been minimized (Steve Shelly, USFS, personal communication). By carefully selecting our study sites we have minimized the potential for exogenous factors to impact radial growth (Soulé and Knapp 2013). On site, we selectively sampled to avoid trees with either obvious physical scars (*e.g.* large fire or lightning scars) or evidence of pathogens such as dwarf mistletoe (*Arceuthobium campylopodum*) or mountain pine beetle (*Dendroctonus ponderosae*). Working in open-canopy woodlands minimizes the potential for growth variation attributed to canopy infilling or senescence of nearby trees. Therefore, we only sampled trees when the canopy did not overlap with another tree and had no infilling from other individuals or species, ensuring competition was not an influence on growth. We non-destructively sampled the trees using increment borers, obtaining a minimum of two core samples/tree at breast height (*i.e.* 1.4 m above ground).

We used standard laboratory techniques (Phipps 1985) to process the cores. We progressively sanded the core samples to reveal cellular structure (Orvis and Grissino-Mayer 2002) and then crossdated the core samples using the list method (Yamaguchi 1991). We measured the samples to 0.001mm using a Velmex© system. We used the program COFECHA (Holmes 1983) for quality control of crossdating and the program ARSTAN (Cook and Holmes 1997) for chronology development standardization and calculation of mean (RAW) growth values. All trees in our chronologies were dated to at least A.D. 1850, thus the negative exponential growth trend over the common period of climate data was small, allowing the comparison of RAW chronologies. We developed two standardized chronologies, one using NegX and one using FRE with the sensitivity level set to five (Friedman 1984). From both we used the STANDARD chronology to correlate with climate, as it has been shown to preserve growth

Table 1. Chronology statistics.

Site	Interseries correlation	Mean sensitivity	# Dated series	Year that signal strength of 0.85 was obtained (# samples) and ending year of chronology
FLR	0.574	0.283	34	1802–2011 (12)
FCR	0.544	0.255	32	1734–2011 (12)
KGR	0.688	0.326	25	1830–2010 (8)
CGR	0.689	0.375	20	1723–2009 (6)

variation that is responsive to changing climate conditions (Buckley *et al*. 2007; Fritts 2012). We also developed chronologies based on mean raw growth values and mean BAI using the Silva *et al.* (2010) formula:

$$\mathrm{BAI} = \pi\left(\mathrm{R}^2{}_{\mathrm{n}} - \mathrm{R}^2{}_{\mathrm{n}-1}\right)$$

where *R* is tree radius and *n* is the year of growth.

We compared the long-term climate response using Pearson correlation between the measures of radial growth and monthly (January–October and prior-year July–December) climatic division-level mean temperature, total precipitation, and Palmer Drought Severity Index (PDSI; Palmer 1965) data (https://www.esrl.noaa.gov/psd/cgi-bin/data/timeseries/timeseries1.pl) from 1905–end of record. We tested for significant differences between the lowest and highest r-values from the four measures of radial growth for each of the three climatic parameters (*i.e.* temperature, precipitation, PDSI) during the month with the strongest climate-growth relationship using the Fisher r-to-z transformation test (Fisher 1915). We examined the temporal stability of the climate-growth relationships using DENDROCLIM2002 and moving-interval analysis (Biondi and Waikul 2004). Specifically, for each study site we chose the month (either concurrent or lagged) that had the strongest overall relationship among the four measures of radial growth for precipitation, temperature, and PDSI and examined the temporal patterns of significant ($p < 0.05$) relationships within 24-year windows. We compared raw radial-growth values among sites using Pearson correlation over the period concurrent with climatic data analyses and examined the raw growth

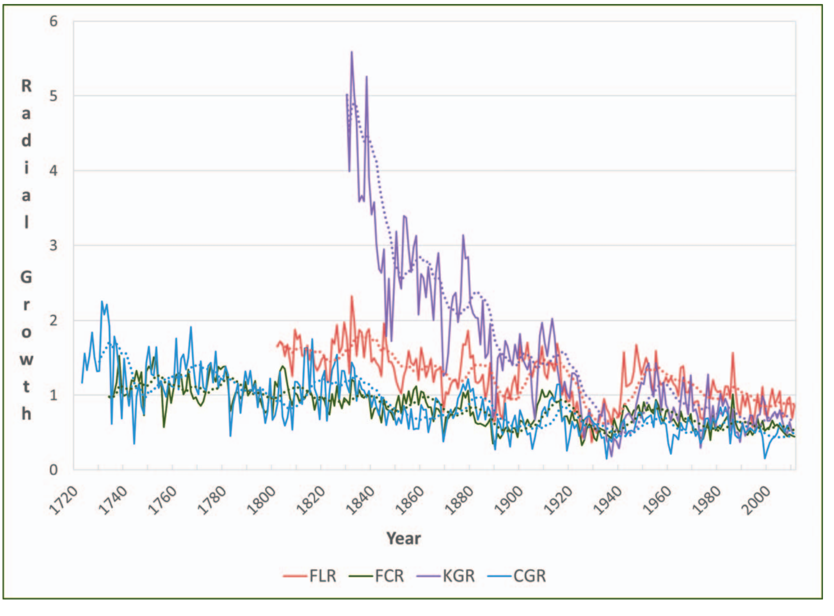

Figure 1. Temporal patterns of raw radial growth (mm) at FLR, FCR, KGR and CGR.

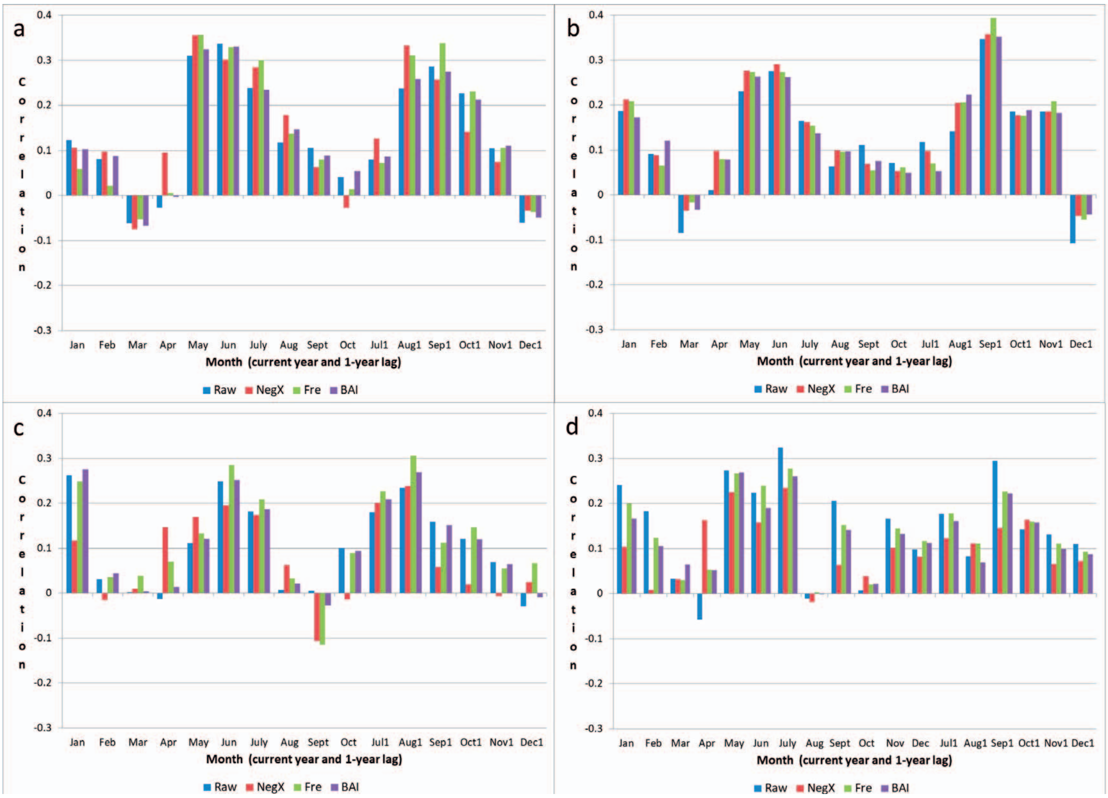

Figure 2. Pearson correlations between total precipitation and radial growth measured by RAW, NegX, FRE, and BAI, by month and 1-year lagged monthly values for FLR (A), FCR (B), KGR (C) and CGR (D) from 1905-end of record (Table 1). Significant ($p < 0.05$) two-tailed relationships begin at $r > 0.19$.

values for the period of record concurrent with an expressed population signal (EPS) > 0.85 (Wigley *et al.* 1984) (Table 1).

RESULTS AND DISCUSSION

Temporal patterns of raw radial growth at the four sites are displayed with a starting point for each chronology determined by the EPS value of 0.85 (signal strength; Table 1) calculated by ARSTAN (Figure 1). Using the time 1905–end of record, which is congruent with our climate analyses, the covariance in raw growth among the four study sites is positive and significant, especially for the three sites located in the same climatic division (Montana Division 1; KGR, FLR, FCR), ranging from $r = 0.473$, $p < 0.05$ (FLR/CGR) to $r = 0.841$, $p < 0.05$ (FLR/FCF), suggesting some region-wide exogenous growth factor (*i.e.* climate) is the driving force behind radial growth, supporting the comparison of RAW chronologies to the other methods for generating growth chronologies.

PIPO radial growth responds positively and consistently across the region to precipitation in both late spring to summer (May–July), and in the prior-year autumn (September–November) (Figure 2). PIPO responds negatively to mid-summer temperature (Figure 3). For the PDSI, which factors in both supply of moisture and demand (via evapotranspiration), the temporal patterns are similar to precipitation, with peak response in current-year spring to summer months, and prior-year autumn months (Figure 4). Overall, July PDSI is the climate variable most closely related to radial growth at FLR, FCR, and CGR, and prior-October PSDI is most closely related at KGR (Figure 4). Raw ring widths have the strongest relationship at two sites (FLR, CGR). NegX is the strongest at FCR,

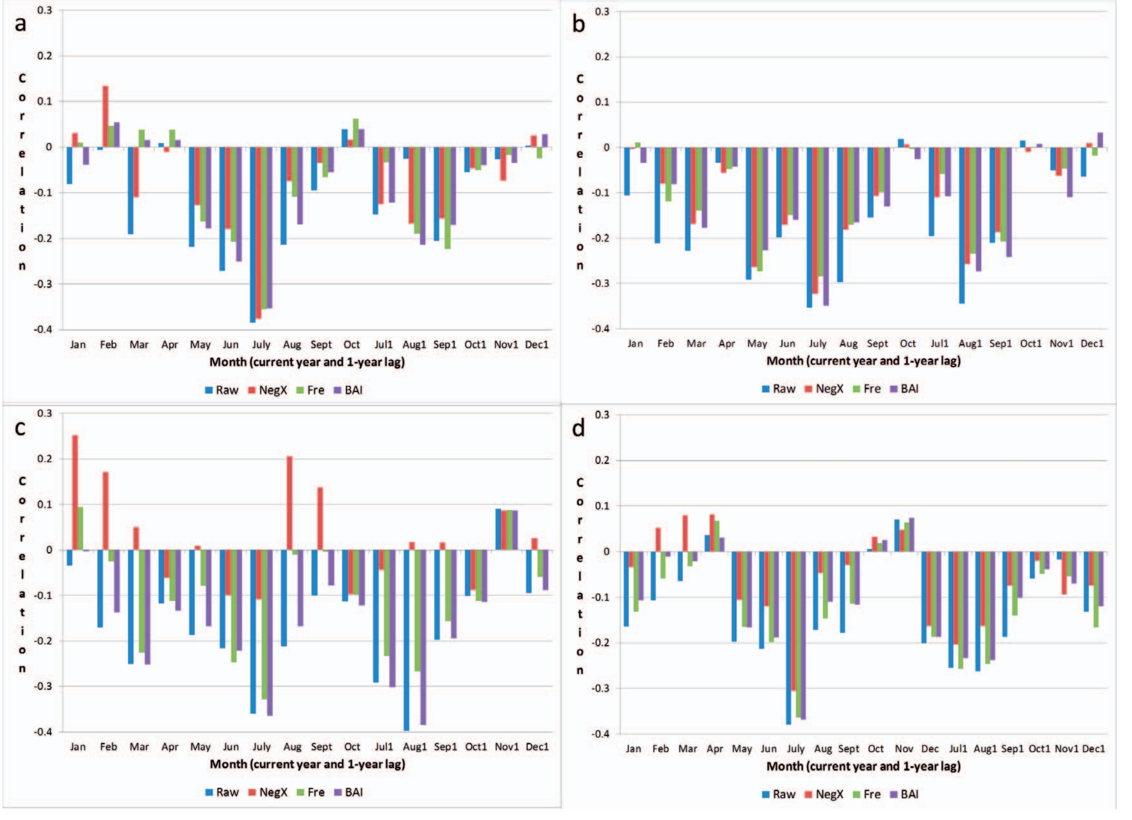

Figure 3. Pearson correlations between mean temperature and radial growth measured by RAW, NegX, FRE, and BAI, by month and 1-year lagged monthly values for FLR (A), FCR (B), KGR (C) and CGR (D)from 1905-end of record (Table 1). Significant ($p <$ 0.05) two-tailed relationships begin at $r > 0.19$.

and BAI at KGR. NegX produces a significantly lower ($p < 0.05$) relationship at KGR for both PDSI (prior October, $r = 0.35$ compared to $r = 0.66$ for BAI) and temperature (prior August, $r = 0.02$ compared to $r = -0.4$ for RAW). NegX also produces a lower correlation at CGR for PDSI (July, $r = 0.36$ compared to $r = 0.61$ for RAW). For all other comparisons, there is no significant difference ($p > 0.05$) in the growth-climate response between the four measures of radial growth.

The weak long-term relationship between drought severity and NegX standardized values at KGR (Figure 4C) appears to be a function of the standardization during the latter portion of the record. Nine of the top-ten growth years via this standardization occurred after 1996 compared to zero, one, and zero years for RAW, FRE, and BAI, respectively, and only 31% of the years after 1996 were matched with positive PDSI values (prior-year October). The 24-year moving interval correlations confirm the relationship with drought severity remained strong and equivalent to the other three measures until the early 2000s (Figure 5C).

The temperature-growth relationship for all sites appears to be impacted by a shorter-term warming trend. For example, July mean temperatures in Montana Climate Division 1 do not have a long-term trend (1905–2009, $r = 0.08$, $p > 0.05$), but in the 30-year period 1980–2009 they are trending upward ($r = 0.46$, $p < 0.05$). Although all sites have stronger relationships earlier in the record (Figure 6), they are predominately insignificant ($p > 0.05$) after the early 1970s. For KGR, the relationships not only weaken, but become weakly positive in the last decade, as high radial growth values are matched with high temperatures, thus

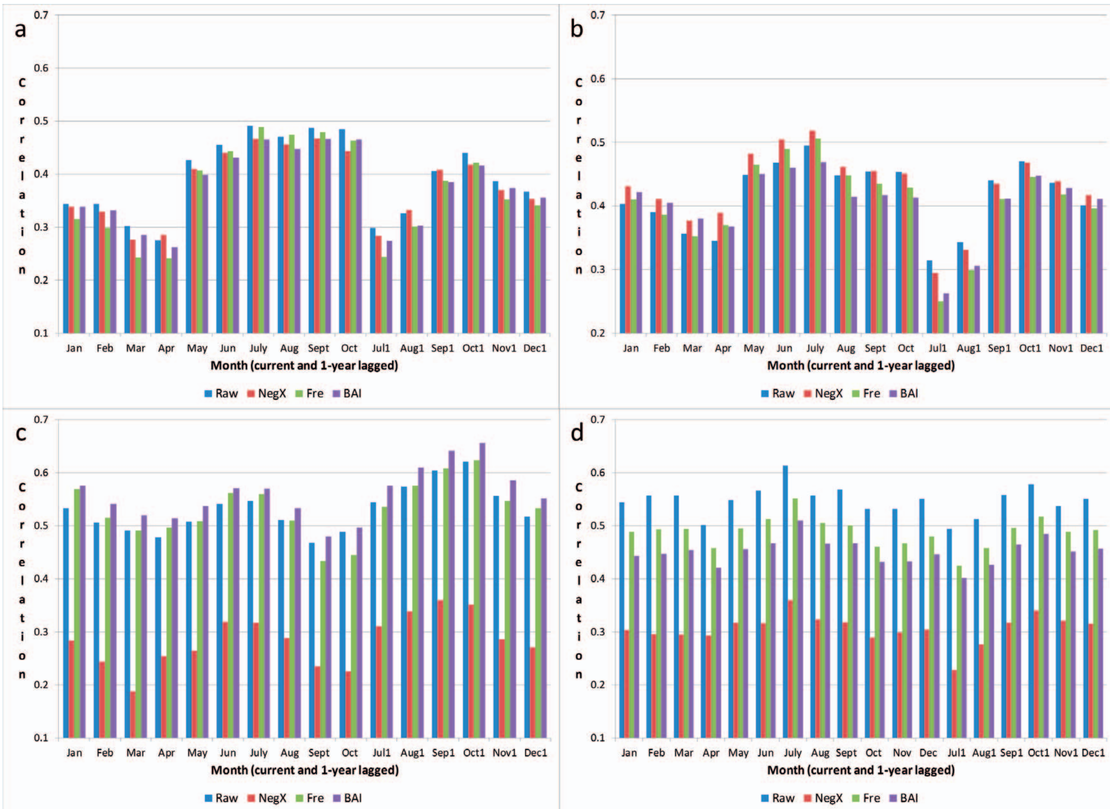

Figure 4. Pearson correlations between PDSI and radial growth measured by RAW, NegX, FRE, and BAI, by month and 1-year lagged monthly values for FLR (A), FCR (B), KGR (C) and CGR (D) from 1905-end of record (Table 1). Significant ($p < 0.05$) two-tailed relationships begin at $r > 0.19$.

weakening the long-term relationship between temperature and radial growth.

For CGR, the moving interval analyses between NegX-standardized radial growth and July PDSI values produced a significant positive correlation for each 24-year window, which was largely in-sync with and sometimes stronger than the other three measures (Figure 5D). However, the long-term relationship was weaker than RAW, FRE, or BAI in all months examined (Figure 4). In this climate division (Montana 4), eight of the top-ten wettest Julys as measured by PDSI were pre-1918, but only one of those years produced a top-ten highest growth value with NegX. For RAW, FRE, and BAI, seven, five and five of those years, respectively, were in the top 10 for wetness. In four of the top-ten growth years for NegX (all after 1995), July PDSI values were negative, and none of the other three measures produced top-ten growth values in those years. The disconnect between shorter-term (*i.e.* 24-year windows) and the longer-term relationship between NegX and July PDSI at CGR is intriguing and appears to be impacted by the greater variance of radial growth produced by NegX (coefficient of variation for long-term radial growth of 30.8%, 33.2%, 29.3%, and 26.9% for RAW, NegX, FRE and BAI, respectively).

In addition to identifying some disconnects between long-term and short-term relationships, the moving-interval analyses also revealed that within-site variation between the four measures of radial growth is minimal, but between-site variation can be large. This is best expressed by the precipitation comparisons (Figure 7), with FLR showing strong relationships early in the record and FCR showing stronger relationships late. Although the monthly pattern for precipitation is similar to PDSI with stronger relationships in summer and

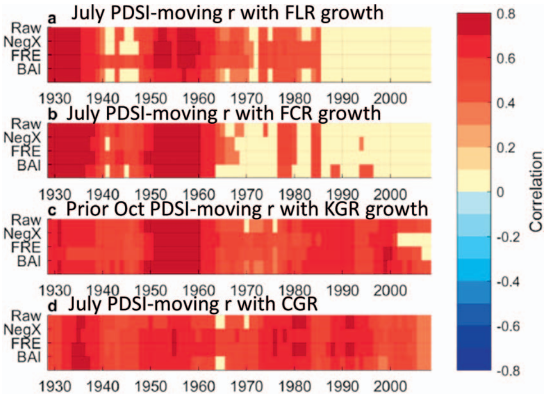

Figure 5. Moving interval correlations between radial tree growth and July PDSI values for FLR (A), July PDSI values for FCR (B), prior year October PDSI values for KGR (C), and July PDSI values for CGR (D). 24-year windows begin in 1905 and end in 2008. Only significant ($p < 0.05$) relationships are shown with the strength of the relationship noted by the red (positive) and blue (negative) color scheme. The horizontally-stacked bars represent the relationship for RAW, NegX, FRE, and BAI at each site.

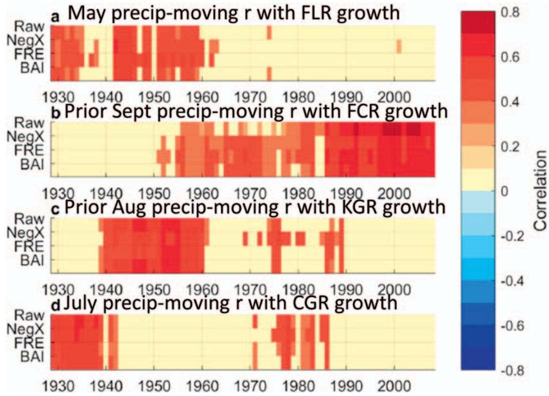

Figure 7. Moving interval correlations between radial tree growth and May total precipitation for FLR (A), prior year September total precipitation for FCR (B), prior year August total precipitation for KGR (C), and July total precipitation for CGR (D). 24-year windows begin in 1905 and end in 2008. Only significant ($p < 0.05$) relationships are shown with the strength of the relationship noted by the red (positive) and blue (negative) color scheme. The horizontally-stacked bars represent the relationship for RAW, NegX, FRE, and BAI at each site.

prior-year autumn, each site was matched with a different month for the 'best' relationship (Figure 2) making the between-site comparisons more volatile.

Our analyses demonstrate that the standardization technique often used on trees growing in semiarid, open-canopy environments (NegX), does not always provide the best solution if the goal is to maximize long-term climatic response. One of the goals of standardization in dendroclimatology is to remove the non-climatic noise and retain the climate response (Speer 2010; Fritts 2012). LaMarche (1974) argued that the use of raw ring widths could sometimes provide a more accurate climate reconstruction because real climatic trends in the data may be removed during the standardization process. However, most climate reconstructions are conducted after standardizing the tree-ring record and LaMarche (1974) was working with long-lived bristlecone pine (*Pinus longaeva*) in a strip-bark growth stage, which is different from our sampled PIPO. In theory, BAI should be superior to RAW for optimizing climate response because it removes the biological growth or 'age trend' (Fritts 2012) contained in the raw ring-width record (Schuster and Oberhuber 2013). If a climate reconstruction was conducted using the RAW chronologies, large differences in the earlier portions of the chronology could occur because of the retention of the biological growth trends (Cook and Holmes 1997; Fritts 2012). However, if the research goal is to simply identify the climate-growth response, then our results from PIPO growing in semiarid western Montana environments suggest that an unstandardized measure of radial growth

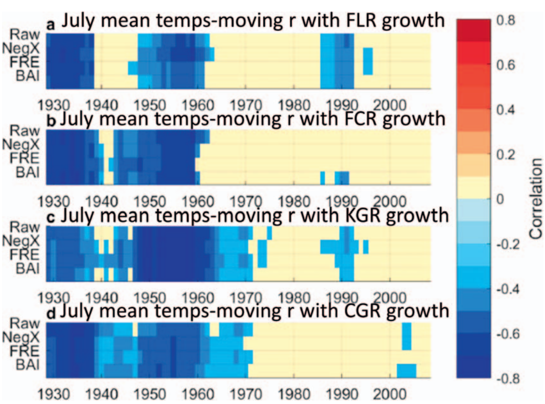

Figure 6. Moving interval correlations between radial tree growth and July mean temperatures at FLR (A), FCR (B), KGR (C), and CGR (D). 24-year windows begin in 1905 and end in 2008. Only significant ($p < 0.05$) relationships are shown with the strength of the relationship noted by the red (positive) and blue (negative) color scheme. The horizontally-stacked bars represent the relationship for RAW, NegX, FRE, and BAI at each site.

can provide either more explanatory power than standardized measures or values that are not significantly different. Specifically, our results show that (1) the commonly used NegX technique does not always produce the strongest climate-growth response, (2) unstandardized measures (RAW, BAI) can provide the strongest climate signal when trees are old enough that the biological growth trend is not large, (3) a more flexible curve fit standardization (FRE) can produce a strong climate-growth response in undisturbed environments (*e.g.* at FLR), (4) with the exception of NegX at KGR and CGR, long-term growth-climate response falls within a narrow range with no significant differences independent of the representation of annual growth, and the strongest climate response can vary among the growth measures between sites, and (5) disconnects between long-term and shorter-term climate growth-relationships can occur and may be related to the standardization technique used. In conclusion, we find that with few exceptions standardization methodologies produce only minor differences in climate-growth relationships and that when using samples from sites where human disturbance is minimal, exploring climate-growth relationships using RAW or BAI units may produce useful results.

REFERENCES CITED

Allen, E. B., T. M. Rittenour, R. J. DeRose, M. F. Bekker, R. Kjelgren, and B. M. Buckley, 2013. A tree-ring based reconstruction of Logan River streamflow, northern Utah. *Water Resources Research* 49:8579–8588.

Bekker, M. F., R. J. DeRose, B. M. Buckley, R. K. Kjelgren, and N. S. Gill, 2014. A 576-year Weber River streamflow reconstruction from tree rings for water resource risk assessment in the Wasatch Front, Utah. *JAWRA Journal of the American Water Resources Association* 50:1338–1348.

Biondi, F., and K. Waikul, 2004. DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. *Computers & Geosciences* 30:303–311.

Biondi, F., and F. Qeadan, 2008. A theory-driven approach to tree-ring standardization: Defining the biological trend from expected basal area increment. *Tree-Ring Research* 64:81–96.

Briffa, K. R., P. D. Jones, F. H. Schweingruber, W. Karlén, and S. Shiyatov, 1996. Tree-ring variables as proxy-climate indicators: Problems with low-frequency signals. In *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, edited by P. D. Jones, R. S. Bradley, and Jean Jouzel, pp. 9–41. Springer, Berlin, Heidelberg.

Buckley, B. M., K. Palakit, K. Duangsathaporn, P. Sanguantham, and P. Prasomsin, 2007. Decadal scale droughts over northwestern Thailand over the past 448 years: Links to the tropical Pacific and Indian Ocean sectors. *Climate Dynamics* 29: 63–71.

Castruita-Esparza, L. U., A. Correa-Díaz, A. Gómez-Guerrero, J. Villanueva-Díaz, M. E. Ramírez-Guzmán, A. Velázquez-Martínez, and G. Ángeles-Pérez, 2016. Basal area increment series of dominant trees of *Pseudotsuga menziesii* (Mirb.) Franco show periodicity according to global climate patterns. *Revista Chapingo. Serie Ciencias Forestales y del Ambiente* 22, no. 3.

Cook, E. R., 1985. *A Time Series Analysis Approach to Tree-Ring Standardization*. PhD dissertation, University of Arizona, Tucson.

Cook, E. R., K. R. Briffa, D. M. Meko, D. A. Graybill, and G. Funkhouser, 1995. The segment length curse in long tree-ring chronology development for palaeoclimatic studies. *The Holocene* 5:229–237.

Cook, E. R., and R. L. Holmes, 1997. ARSTAN: Chronology development. In *The International Tree-Ring Data Bank Program Library, Version 21 User's Manual*, edited by Grissino-Mayer, H. D., R. L. Holmes, and H. C. Fritts, pp. 75–92. University of Arizona Laboratory of Tree-Ring Research, Tucson, Arizona.

Cook, E. R., and K. Peters, 1997. Calculating unbiased tree-ring indices for the study of climatic and environmental change. *The Holocene* 7:361–370.

Devineni, N., U. Lall, N. Pederson, and E. R. Cook, 2013. A tree-ring-based reconstruction of Delaware River Basin streamflow using hierarchical Bayesian regression. *Journal of Climate* 26:4357–4374.

Fisher, R. A., 1915. Frequency distribution of the values of the correlation coefficient in samples of an indefinitely large population. *Biometrika* 10:507–521.

Friedman, J. H., 1984. *A Variable Span Smoother*. Laboratory for Computational Statistics, Department of Statistics, Stanford University, Stanford, CA. Technical Report 5

Fritts, H. C., 2012. *Tree Rings and Climate*. Elsevier. (Originally published 1976, Academic Press, London.)

Grissino-Mayer, H. D., 1996. A 2129-year reconstruction of precipitation for northwestern New Mexico, USA. *Tree Rings, Environment, and Humanity*, edited by J. S. Dean, D. M. Meko, and T. W. Swetnam, pp. 191–204. Radiocarbon, Tucson, Arizona.

Grissino-Mayer, H. D., and T. W. Swetnam, 2000. Century-scale climate forcing of fire regimes in the American Southwest. *The Holocene* 10:213–220.

Helama, S., M. Lindholm, M. Timonen, and M. Eronen, 2004. Detection of climate signal in dendrochronological data analysis: A comparison of tree-ring standardization methods. *Theoretical and Applied Climatology* 79:239–254.

Holmes, R. L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43:69–78.

Holmes, R. L., R. K. Adams, and H. C. Fritts, 1986. *Tree-Ring Chronologies of Western North America: California, Eastern Oregon and Northern Great Basin with Procedures Used in the Chronology Development Work Including Users Manuals for Computer Programs COFECHA and ARSTAN*. Laboratory of Tree-Ring Research, University of Arizona, Tucson.

IBM Corp., 2016 (release). *IBM SPSS Statistics for Windows, Version 24.0*. IBM Corp., Armonk, New York.

Knapp, P. A., and P. T. Soulé, 2011. Increasing water-use efficiency and age-specific growth responses of old-growth ponderosa pine trees in the Northern Rockies. *Global Change Biology* 17:631–641.

Knapp, P. A., P. T. Soulé, and J. T. Maxwell, 2013. Mountain pine beetle selectivity in old-growth ponderosa pine forests, Montana, USA. *Ecology and Evolution* 3:1141–1148.

LaMarche, V. C., 1974. Paleoclimatic inferences from long tree-ring records. *Science* 183(4129):1043–1048.

McKenzie, D., A. E. Hessl, and D. L. Peterson, 2001. Recent growth of conifer species of western North America: Assessing spatial patterns of radial growth trends. *Canadian Journal of Forest Research* 31:526–538.

Orvis, K. H., and H. D. Grissino-Mayer, 2002. Standardizing the reporting of abrasive papers used to surface tree-ring samples. *Tree-Ring Research* 58:47–50.

Palmer, W., 1965. *Meteorological Drought*. US Government Printing Office, Washington, DC.

Pederson, N., A. R. Bell, T. A. Knight, C. Leland, N. Malcomb, K. J. Anchukaitis, K. Tackett, J. Scheff, A. Brice, B. Catron, W. Blozan, and J. Riddle, 2012. A long-term perspective on a modern drought in the American Southeast. *Environmental Research Letters* 7:014034. http://dx.doi.org/10.1088/1748-9326/7/1/014034.

Phipps, R. L., 1985. *Collecting, Preparing, Crossdating, and Measuring Tree Increment Cores*. US Department of the Interior, Geological Survey Water-Resources Investigations Report 85-4148; 48 pp.

Salzer, M. W., and K. F. Kipfmueller, 2005. Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, USA. *Climatic Change* 70:465–487.

Schuster, R., and W. Oberhuber, 2013. Age-dependent climate–growth relationships and regeneration of *Picea abies* in a drought-prone mixed-coniferous forest in the Alps. *Canadian Journal of Forest Research* 43:609–618.

Silva, L. C., M. Anand, and M. D. Leithead, 2010. Recent widespread tree growth decline despite increasing atmospheric CO_2. *PLoS ONE* 5:11543. doi:10.1371/journal.pone.0011543.

Soulé, P. T., and P. A. Knapp, 2006. Radial growth rate increases in naturally occurring ponderosa pine trees: A late-20th century CO_2 fertilization effect? *New Phytologist* 171: 379–390.

Soulé, P. T., and P. A. Knapp, 2013. Radial growth rates of two co-occurring coniferous trees in the Northern Rockies during the past century. *Journal of Arid Environments* 94: 87–95.

Soulé, P. T., and P. A. Knapp, 2015. Analyses of intrinsic water-use efficiency indicate performance differences of ponderosa pine and Douglas-fir in response to CO_2 enrichment. *Journal of Biogeography* 42:144–155.

Speer, J. H., 2010. *Fundamentals of Tree-Ring Research*. University of Arizona Press, Tucson.

Villanueva, D. J., and G. R. McPherson, 1996. Reconstruction of precipitation and PDSI from tree-ring chronologies developed in the mountains of New Mexico, USA and Sonora, Mexico. In *Proceedings of the 1996 Meeting of the Hydrology Section, Arizona-Nevada Academy of Science* 26:45–54.

Wigley, T. M., K. R. Briffa, and P. D. Jones, 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology* 23:201–213.

Received 19 October 2017; accepted 5 October 2018.