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LATEWOOD CHRONOLOGY DEVELOPMENT FOR SUMMER-MOISTURE RECONSTRUCTION IN THE US SOUTHWEST

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ABSTRACT

Tree-ring studies have demonstrated that conifer latewood measurements contain information on long-term North American monsoon (NAM) variability, a hydroclimatic feature of great importance to plants, animals, and human society in the US Southwest. This paper explores data-treatment options for developing latewood chronologies aimed at NAM reconstruction. Archived wood samples for five Douglas-fir (*Pseudotsuga menziesii,* Mirb. Franco) sites in southeastern Arizona are augmented with new collections. The combined dataset is analyzed along with time series of regionally averaged observed precipitation to quantify the strength of regional precipitation signal in latewood time series and to identify ways of increasing the signal strength. Analysis addresses the signal strength influences of including or excluding "false" latewood bands in the nominal "latewood" portion of the ring, the necessary adjustment of latewood width for statistical dependence on antecedent earlywood width, and tree age. Results suggest that adjusted latewood width chronologies from individual sites can explain around 30% of the variance of regional summer (July–August) precipitation—increasing to more than 50% with use of multiple chronologies. This assessment is fairly insensitive to the treatment of false latewood bands (in intra-annual width and $\delta^{13}C$ variables), and to whether latewood-width is adjusted for dependence on earlywood-width at the core or site level. Considerations for operational chronology development in future studies are (1) large tree-to-tree differences in moisture signal, (2) occasional nonlinearity in EW-LW dependence, and (3) extremely narrow and invariant latewood width in outer portions of some cores. A protocol for chronology development addressing these considerations is suggested.

Keywords: Latewood, chronology development, Douglas-fir, *Pseudotsuga menziesii*, North American monsoon, summer precipitation, Arizona, false rings, carbon isotopes.

INTRODUCTION

The North American monsoon (NAM) is a predominant climatic feature in northern Mexico and the US Southwest characterized by large-scale changes in pressure, wind, and water vapor that translate to local-scale convective thunderstorms across the region during the warm season (Adams and Comrie 1997). The NAM contributes up to 60% of the annual precipitation in parts of the US Southwest, and is a critical factor in maintaining the region's ecosystems that rely on a bimodal precipitation regime. The NAM influences natural fire dynamics (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000) and modulates demand for urban and agricultural water supplies (Ray *et al.* 2007). Spatiotemporal variability in monsoon precipitation has been the topic of extensive research in recent decades (*e.g.* Carleton and Carpenter 1990; Douglas *et al.* 1993; Comrie and Glenn 1998; Gutzler 2000; Higgins and Shi 2000; Castro *et al.* 2001; Zhu *et al.* 2005; Higgins and Gochis 2007; Liebmann *et al.* 2008; Turrent and Cavazos 2009), and robust information on monsoon variability has implications for natural resources management (Ray *et al.* 2007). The research described here is part of a larger study aimed at development of the first large-scale network of NAM precipitation-sensitive chronologies in the US Southwest.

Although most dendroclimatic studies in the interior Southwest have targeted cool-season or

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annual precipitation (*e.g.* D'Arrigo and Jacoby 1991; Grissino-Mayer 1996; Meko 1997; Woodhouse and Meko 1997; Ni *et al.* 2002; Cleaveland *et al.* 2003; Salzer and Kipfmueller 2005; Villanueva-Diaz *et al.* 2007; Touchan *et al.* 2010), dendrochronologists have long recognized the potential of intra-annual ring-width (hereafter 'partial width') measurement for summer-season climate information (Douglass 1919; Schulman 1942, 1951; Winter 1976; Cleaveland 1986, 1988). Several recent southwestern studies have reconstructed monsoon-specific moisture conditions using measurements of "earlywood width" (EW) and "latewood width" (LW). For this work, earlywood is defined as the lighter-colored, less-dense component of the annual ring, whereas latewood is defined as the darker-colored, more-dense component that is visually discernable and often characterized by an abrupt anatomical transition from antecedent earlywood.

Partial-width measurements can be rapidly obtained by well-trained technicians using a Velmex measurement system and simple visual criteria for determination of the boundary between EW and LW width. This is an attractive alternative to methods such as X-ray densitometry (Schweingruber *et al.* 1978; Cleaveland 1986, 1988) and reflected light densitometry (Sheppard and Wiedenhoeft 2007; Babst *et al.* 2009), which require extensive sample preparation and are challenged by the micro-rings and missing rings that are common in semi-arid sites around the Southwest.

Meko and Baisan (2001) applied a binary classification-tree model to categorize summers as wet or dry from adjusted latewood-width (hereafter, LW_a) index chronologies from conifers in southeastern Arizona. The "adjustment" consisted of removing the LW's systematic dependence on antecedent EW using linear regression, isolating the variability unique to the LW, which substantially enhanced the summer moisture signal. Therrell *et al.* (2002) showed that LW chronologies in Mexico contain a signal related to large-scale monsoon onset. Stahle *et al.* (2009) reconstructed 2,136 years of July precipitation in northwestern New Mexico from a single LW_a chronology. Leavitt *et al.* (2002, 2011) found a NAM moisture signal in stable carbon ($^{13}C/^{12}C$; hereafter $\delta^{13}C$) isotope analysis of latewood cellulose. Sheppard and Wiedenhoeft (2007) demonstrated the utility of reflected light analysis in extracting summer-moisture signal from the latewood of conifers in New Mexico.

Previous studies raise several questions about the operational large-scale application of latewood measurements to summer-rainfall reconstruction and NAM analysis. The first regards how the partial-width components should be defined for this objective when distinct intra-annual wood-density variations known as "false rings" are present (Figure 1). All known studies are consistent in using the first false latewood band as a marker separating EW and LW, but disagree on assignment of the band itself to EW or LW. Schulman (1951:25) described the phenomena but was not precisely clear about whether the first latewood band should be included in the EW or LW: "A somewhat arbitrary criterion had to be set up for the amount of latewood in the numerous rings which included false bands. Because experience elsewhere in the Southwest had indicated that false rings were related to the July and, to a lesser extent, the August rains, and because the onset of normal latewood growth in the timber conifers is in July, all growth following the first latewood cells was classed as latewood, no matter how apparently complete the return to earlywood type before the final cells of the season were laid down". Winter (1976:46) followed Schulman's 1951 "suggestion" and measured LW "from the earliest occurrence of small, dense cells". Stahle *et al.* (2000) and Stahle *et al.* (2009:3734) mark the EW-LW boundary "at the first onset of lumen contraction (*i.e.* all false rings are measured as part of the LW)". In contrast, Meko and Baisan (2001, personal communication) and Leavitt *et al.* (2002) include the first false latewood band in the EW, citing Arizona studies that attribute false-ring formation to moisture changes from the cool season through the routinely dry "fore-summer" period of May–June that precedes the onset of the summer monsoon (Douglass 1919; Zahner 1963; Fritts 2001; Baisan and Swetnam 1994). The two partial-width marking rules are referred to hereafter as MB2001 (Meko and Baisan 2001) and ST2009 (Stahle *et al.* 2009).

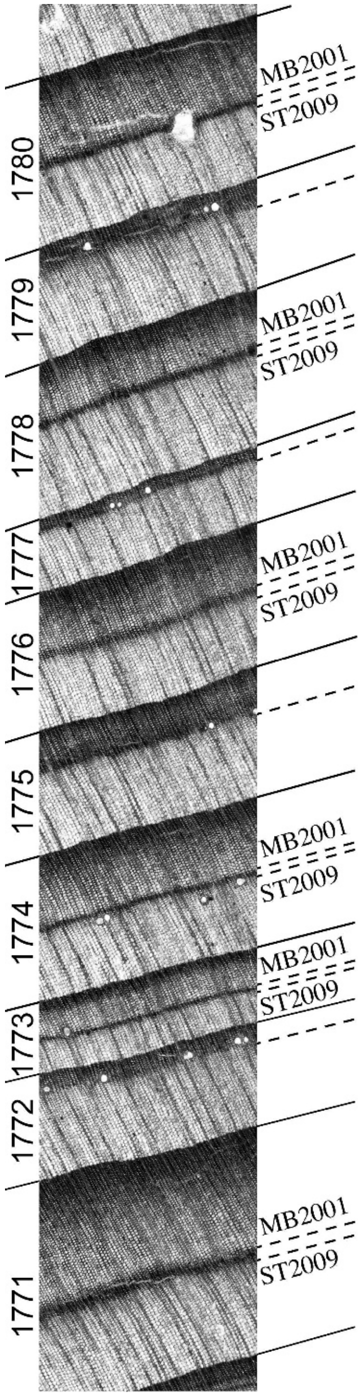

Figure 1. Photomicrograph illustrating growth rings for the years 1771–1780 on a Douglas-fir increment core from site PRM. Solid lines indicate annual boundaries and dashed lines indicate the visually identified EW-LW boundary as marked by Meko and Baisan (2001) ("MB2001") and Stahle *et al.* (2009) ("ST2009"). Both use the earliest false ring to delineate the EW-LW boundary, the former including the first false latewood band in the EW measurement, and the latter including it in the LW measurement.

A second question relates to the appropriate procedure for adjusting LW for dependence on antecedent EW. Meko and Baisan (2001) found that removal of this dependence is key to the extraction of a summer-rainfall signal, and did so by linear regression of site-chronology LW indices on site-chronology EW indices. The same approach was followed by Stahle *et al.* (2009). Scatterplots of LW index on EW index for individual cores from conifers in Arizona have revealed much tree-to-tree variation in the dependence. Improved site chronologies for summer-rainfall reconstruction might therefore be possible if the dependence of LW on EW was modeled and removed at the core-level instead of the site-level.

A third question is the possible importance of tree age to strength of the summer-moisture signal in LW. LW, like total width (TW), typically decreases with increasing tree age. The decrease of LW with age can be extremely steep, however, and the LW can become extremely narrow and nearly invariable from year-to-year in the outer portions of some cores. Winter (1976), Meko and Baisan (2001), Therrell *et al.* (2002), and Stahle *et al.* (2009) recognized this problem and addressed it by excluding the outside segments of problematic cores from LW chronology development; these authors advocate including young to middle-aged trees (*e.g.* 100–250 yr-old) throughout the chronology. Until now, however, no attempt has been made to quantify the age-dependence of the LW signal for summer moisture, or to develop an objective procedure for screening and truncation of problematic cores.

In the paper we address the challenges described above with observed precipitation and tree-ring data from selected Douglas-fir (*Pseudotsuga menziesii,* Mirb. Franco) sites in southeastern Arizona. We quantify the strength of summer-moisture signal at the level of the individual core and site chronology, and assess the sensitivity of

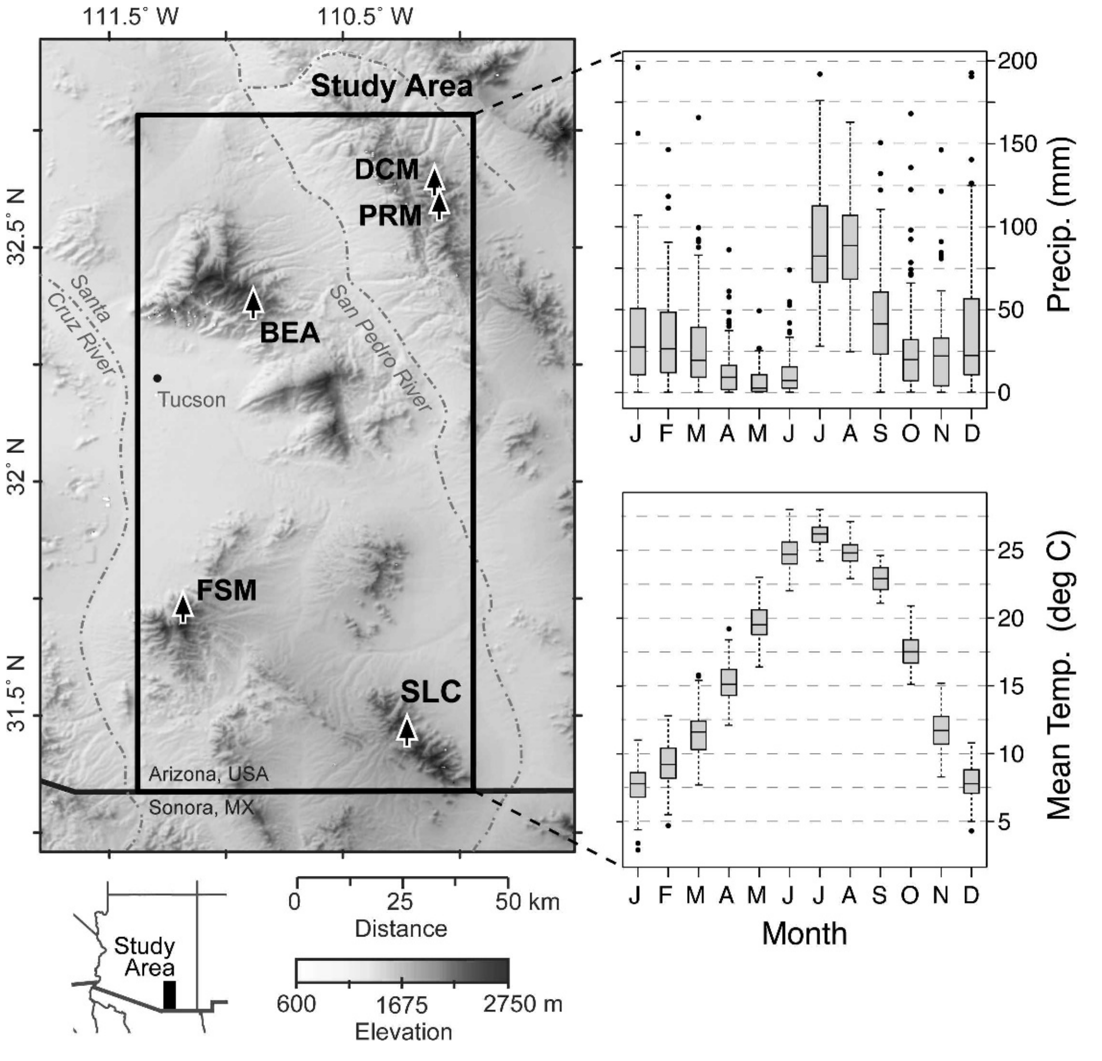

Figure 2. Site locations and regional climatogram. Map shows the study area in southeastern Arizona, including the locations of the tree-ring collections measured for partial width (DCM, FSM, PRM, SLC) and for $\delta^{13}C$ (BEA). Black box indicates the area for which PRISM climate data were obtained for sensitivity analyses. Climatogram uses box and whisker plots to illustrate the distribution of monthly precipitation and temperature for the period 1895–2008. Each box bounds the interquartile range with the median illustrated as the horizontal line. Whiskers extend to the data within 1.5 q of the box where q is the interquartile range. Black dots are outliers.

the signal to (1) rule in marking of the earlywood-latewood boundary, (2) adjustment of LW for dependence on antecedent EW at the core level *versus* site level, and (3) tree age. We also propose a protocol for objective identification and screening of problematic LW series. A small component of the work addresses the sensitivity of the latewood cellulose $\delta^{13}C$ relative to the rule used in marking the earlywood-latewood boundary.

DATA AND METHODS

Tree-Ring Data

Douglas-fir increment-core collections from five sites in southeastern Arizona are used in this study (Figure 2; Table 1). Partial ring widths were analyzed for four collections (Table 1; DCM, PRM, FSM, SLC). Samples were collected from four trees for latewood $\delta^{13}C$ at the fifth site, BEA.

Table 1. Tree-ring site information.

Site Code[a]	Site Name	Latitude (°N)	Longitude (°W)	Elevation (M)	Variable Measured	No. of Trees	No. of Radii	MSSL[b]
FSM	Florida Saddle	31.723	110.839	2,385	partial width	55	94	190
DCM	Douglas Canyon	32.627	110.298	2,074	partial width	41	69	150
PRM	Paddy's River	32.586	110.283	2,252	partial width	40	71	185
SLC	Scheelite Canyon	31.461	110.355	1,812	partial width	48	72	135
BEA	Bear Canyon	32.377	110.685	1,877	latewood $\delta^{13}C$	4	8	10

[a] Three letter code, as in Figure 2.
[b] Mean sample segment length (years).

The wood samples used for width analysis are a combination of new collections made in the spring of 2009 and archived wood specimens housed at the Laboratory of Tree-Ring Research from previous dendroclimatic studies. Middle-aged (*i.e.* 100 to 250 yr-old) and young trees (*i.e.* less than 100 yr-old) were specifically included in the new collections to evaluate the potential influence of tree age on moisture sensitivity of LW.

Specimens were prepared and crossdated with standard dendrochronological methods (*e.g.* Stokes and Smiley 1996). EW, LW, and TW were measured to an accuracy of 0.001 mm with a Velmex system using both the MB2001 and ST2009 rules for the EW-LW boundary. The boundary was determined optically under the microscope by measuring technicians guided by templates of microphotographs illustrating the MB2001 and ST2009 marking rules (*e.g.* Figure 1). Crossdating and measurement accuracy were verified with program COFECHA (Holmes 1983; Grissino-Mayer 2001). Prior to standardization, as described by Therrell *et al.* (2002) and Stahle *et al.* (2009), precisely dated LW segments and series that were identified by COFECHA as exhibiting low correlation with the other series were excluded from the subsequently calculated site-level chronologies.

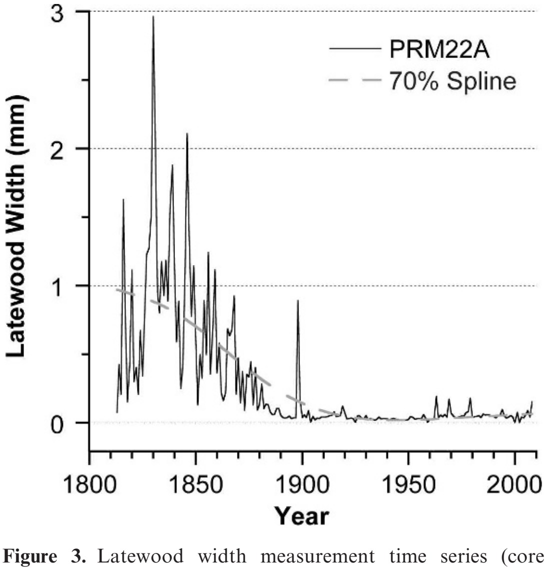

Figure 3. Latewood width measurement time series (core PRM22A) that was dropped from the study because the latewood width was thin, little-varying, and poorly correlated with the other series from the site. Dashed line is fitted 70% spline (Cook and Peters 1981).

The archive specimens had previously been crossdated, but required measurement of partial widths. Archive specimens were selected that exhibited visually strong LW variability over time, and the outer portions of cores with extremely thin, relatively invariant latewood width or with a high frequency of missing rings after 1950 were excluded from this analysis (Figure 3). This screening step frequently identified the same problematic cores as in the COFECHA analysis. For example, the core illustrated in Figure 3 also has a drop in 50-year windowed correlations with its COFECHA master from 0.70 before 1899 to less than 0.11 after 1925.

Measured ring-width series of TW, EW and LW were detrended with a cubic smoothing spline whose frequency response is 0.5 at a wavelength equal to 70% of the length of the measured series (Cook and Peters 1981). Core indices were computed as the ratio of measured width to the corresponding value of this "70% spline". Pooled autocorrelation was modeled and removed from the individual EW and LW index time series by autoregressive modeling (Box and Jenkins 1976; Meko 1981) to produce "residual" core-level indices.

Adjusted-LW index was computed as in previous studies (Meko and Baisan 2001; Stahle *et al.* 2009) as the residual from a linear regression of LW index on antecedent EW index. Because exploratory scatter plots of LW index on EW index occasionally exhibited pronounced curvature, we modified this procedure to allow a quadratic term to enter the regression, as long as the resulting regression coefficients on both the linear and quadratic term were positive. This constraint is consistent with the observation from individual scatter plots that organized patterns of curvature were typically concave-upward. If either of the estimated regression coefficients were negative, a purely linear model was used for the adjustment, and in that case the slope of the fitted line was not restricted to be positive.

Robust bi-weight mean chronologies of TW, EW, LW and adjusted LW were computed for each site by averaging over cores (Cook *et al.* 1990). To summarize the strength of common growth signal, the effective chronology signal (Briffa and Jones 1990; equation 3.43) was calculated for each version of the chronology. Adequacy of sample size for capturing the hypothetical population growth signal was assessed by the expressed population signal (EPS; Briffa 1984; Wigley *et al.* 1984); a threshold EPS of 0.85 was used to delineate the "critical year", when sample depth becomes adequate for capturing the population signal.

Standardization by the procedure just described revealed two problematic features of LW that required special treatment for some cores. First is the rare (only 3 of 306 cores) phenomenon of the fitted 70% spline dipping to zero or below in response to an especially steep decline in LW. For such series the ring-width series was truncated to end 10 years before the growth curve dropped below zero, and the series was re-fit with a 100-year spline (Cook and Peters 1981).

The second problematic feature of some LW series was clear tracking of a known recent low-frequency climate fluctuation by the 70%-spline growth curve when fit to short ring-width series from the young-tree samples: the spline for series beginning in the 1940s or 1950s typically had a strong upward trend out of the well-documented and persistent 1950s drought (Thomas 1962). Such short samples, though probably not relevant to operational climate reconstruction, are important to the assessment of possible age-dependence in climate signal. To avoid removing this predominant climate signal in standardization, we fit such series with a horizontal line at the mean ring-width rather than with a 70% spline.

The $\delta^{13}C$ analysis was limited to a short sequence of ten rings (1999–2008) from four young (55 to 80 yr-old) trees at site BEA. Latewood cellulose was isolated for $\delta^{13}C$ analysis with the techniques described by Leavitt *et al.* (2002). Increment cores were split longitudinally to provide two samples (MB2001 and ST2009 marking rules) from each core for each year. For each tree, latewood cellulose samples pooled from two cores were combusted to CO_2 in an elemental analyzer, which was introduced into a Finnigan Delta-Plus mass-spectrometer in flow-through mode at the Environmental Isotope Laboratory, University of Arizona, with procedure and standards as described in Panyushkina *et al.* (2008). Analytical precision for repeat analysis of the working standard (highly-homogenized commercial cellulose) is *ca.* 0.09‰. The $\delta^{13}C$ series, though too short for rigorous statistical analysis, were examined for any large and systematic differences in $\delta^{13}C$ when partial-width boundaries are delineated by the MB2001 and ST2009 marking rules. Three of the 80 samples were lost in preparation and analysis, so comparison of the MB2001 and ST2009 marking rules was possible for 37 of the 40 pairs.

Climate Data

Monthly total precipitation and mean temperature data used in this study are from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) gridded dataset, as described in detail by Daly *et al.* (2008). PRISM data for the period 1895–2008 were obtained from the Western Climate Mapping Initiative (WestMap) website (http://www.cefa.dri.edu/Westmap/; last accessed February 27, 2011) for the rectangular area bound by the northwestern coordinate of 32.784°N, 110.939°W and the southeastern coordinate of 31.339°N, 110.221°W, which encompasses the four mountain ranges from which the tree-ring data originate (Figure 2). The climatogram presented in Figure 2 illustrates the range of monthly precipitation and mean monthly temperature for this region in the period 1895–2008. Note the distinct mode of precipitation in July–August related to the North American monsoon, and the warm dry fore-summer period of May–June immediately preceding monsoon onset in the region.

Sensitivity Analysis

Correlation analysis was used to summarize the seasonal precipitation signal in total-width and partial-width indices, including the sensitivity of the signal to several data-processing options in chronology development. For each of the four partial width sites, cool-season (October–April) and summer (July–August) precipitation sums, 1896–2008, were correlated with four different versions of residual site chronologies of TW, EW and LW computed by combinations of the following options:

1. MB2001 or ST2009 rule for marking the boundary between earlywood and latewood
2. Adjustment of LW for dependence on antecedent EW at the individual-core level or the site level.

Correlations between July–August precipitation and adjusted-LW indices for individual cores were also computed to summarize the variability in strength of summer moisture signal among trees. The analysis was restricted to the set of partial-width measurements completed with the MB2001 marking rule. Correlations were computed for the period 1937–1986, a fifty-year period common to the greatest number of LW series, and assessed using four age classes (50–99, 100–199, 200–299, and 300–389 yr). Of particular interest in this analysis was the possible dependence of moisture-signal on tree age. Age-dependence identified by this correlation analysis is residual in the sense that the initial visual screening of archive cores for prominent and variable LW by COFECHA for strong common signal may preferentially eliminate old trees or outer segments of their cores.

Finally, the partial- and total-width chronologies computed with the techniques determined to be optimal were correlated to monthly and seasonal climate data over the full instrumental period to characterize the general climate sensitivity of partial-width indices in the study area.

RESULTS AND DISCUSSION

LW Chronology Strength

The common growth-signal in the LW and LW_a indices is considerably lower than that in EW and TW at the four sites, as measured by the effective chronology signal ($\bar{r}_{eff}$) and EPS statistics (Table 2). Statistic $\bar{r}_{eff}$, which is roughly analogous to a mean between-tree correlation, ranges from 0.33 to 0.46 for the two types of LW index, compared with 0.56–0.62 for TW index and 0.58–0.65 for EW index. The results indicate a systematically noisier common signal in LW than in EW, and further that the common signal in TW is degraded somewhat by the noise in the LW. The weaker common signal in LW and LW_a translates to a smaller EPS and indicates the need for a greater sample-size requirement to capture the population growth signal. For the four sites studied, 8–11 trees comprise an adequate sample size for adjusted-LW, while only 4–5 trees are required for EW. The difference in signal strength at site DCM leads to a difference in the length of usable site chronology (*e.g.* for climatic reconstruction) of 97 years.

Treatment of False Latewood Band

The MB2001 marking rule yielded higher correlations than the ST2009 rule at three sites for correlation of LW_a with summer precipitation, with a maximum difference of 0.082 (site FSM, site-level adjustment version; Table 3). The consistency in sign of the change in correlation

Table 2. Summary statistics of common-growth signal strength in total- and partial-width chronologies at four tree-ring sites. Analysis uses version of LW_a by MB2001 marking rule.

Site	Type[a]	$\bar{r}_{eff}$ [b]	No. of Trees[c]		Year[d]		
			Max	Crit	First	Last	Crit
DCM	TW	0.62	35	4	1654	2008	1668
DCM	EW	0.64	35	4	1654	2008	1667
DCM	LW	0.42	35	8	1654	2008	1764
DCM	LW_a	0.42	35	8	1654	2008	1763
FSM	TW	0.60	49	4	1601	2008	1627
FSM	EW	0.65	49	4	1601	2008	1627
FSM	LW	0.39	49	9	1601	2008	1641
FSM	LW_a	0.38	49	10	1601	2008	1646
PRM	TW	0.58	39	5	1607	2008	1676
PRM	EW	0.58	39	5	1607	2008	1676
PRM	LW	0.46	38	7	1607	2008	1684
PRM	LW_a	0.43	38	8	1607	2008	1688
SLC	TW	0.56	44	5	1632	2009	1745
SLC	EW	0.65	44	4	1632	2009	1723
SLC	LW	0.33	40	12	1632	2009	1809
SLC	LW_a	0.34	40	11	1632	2009	1792

[a] Chronology type: total width (TW), earlywood width (EW), latewood width (LW), or adjusted latewood width (LW_a).
[b] Effective chronology signal, as defined in text.
[c] Maximum number of trees in any year (Max) and number of trees (Crit) needed for the critical expressed population signal (EPS) threshold of 0.85.
[d] First and last year with any tree-ring data and critical year (first year with EPS $\geq$ 0.85).

suggests the MB2001 as the preferred marking rule if the objective is summer-precipitation reconstruction. However, a test of difference of correlation (Snedecor and Cochran 1989) indicates that the difference of 0.082 is not statistically significant at $\alpha = 0.05$. For the listed correlation of $r = 0.51$ at site FSM by the ST2009 marking rule, the correlation would need to be higher than $r = 0.68$ by the MB2001 rule for the *difference* in r to be significant at $\alpha = 0.05$. We also note for all four sites the ST2009 rule gives slight improvement over MB2001 in correlation of cool-season precipitation with EW. Perhaps some additional seasonal climate information, as yet unidentified,

Table 3. Pearson correlation coefficients of partial-width chronologies with seasonal precipitation, 1896–2008. All coefficients significant at the 99.9% confidence level.

Type[a]	Measurement[b]	Adjustment	Site[c]				
			DCM	FSM	PRM	SLC	Average
EW	MB2001	N/A	0.603	0.687	0.560	0.727	0.710
EW	ST2009	N/A	0.616	0.717	0.680	0.730	0.744
LW_a	MB2001	Site	0.636	0.592	0.502	0.549	0.725
LW_a	MB2001	Core	0.624	0.580	0.520	0.547	0.724
LW_a	ST2009	Site	0.606	0.510	0.542	0.501	0.662
LW_a	ST2009	Core	0.595	0.499	0.540	0.503	0.653

[a] Chronology type: earlywood width (EW) and adjusted latewood width (LW_a).
[b] Marking rule used to identify boundary between earlywood and latewood, as described in text and illustrated in Figure 1.
[c] Correlations of partial-width index chronologies from individual sites and the average of the four sites with regional-average precipitation totals for their corresponding seasons (October–April for EW, July–August for LW_a).

is present in the discontinuous series of false-latewood band widths. Including that band in the LW degrades the LW signal for summer precipitation, whereas including the band in the EW degrades the EW signal for cool-season precipitation. Including a dummy variable of false ring presence or absence might improve calibration and verification statistics in regression-based climate reconstruction, as in Wimmer *et al.* (2000).

Practically, the choice of one marking rule over another has greatest implications for tree-ring collections with a high frequency of false rings such as the specimen illustrated in Figure 1. Numerous reports have focused on the meteorological and climatic significance of false rings, as reviewed in part by Edmondson (2010). Further investigations are needed in the Southwest, but the available field-based observations of tree phenology from this area suggest that false rings form during the pre-monsoon May–June drought that is characteristic of the region's climate (Baisan and Swetnam 1994; Fritts 2001). As early as 1919, Douglass published this hypothesis, also noting that "double" rings were most common in years of exceptionally poor snowpack. If the timing of false ring formation does indeed correspond to the period leading up to monsoon onset, these phenomena provide an advantageous anatomical delimiter for the growth that occurs during the monsoon months.

The choice of marking rule for segmenting earlywood and latewood likewise was found to make no statistically significant difference to the $\delta^{13}C$ values. Latewood cellulose segmented by the MB2001 rule produced average $\delta^{13}C$ values that were highly correlated ($r = 0.964$) with those developed from latewood segmented by the ST2009 rule (Figure 4). A high correlation was expected because wood samples analyzed by two methods differ only in thickness of the first false ring, if present. As illustrated by error bars in Figure 4, between-tree variations in $\delta^{13}C$ values exceed those observed between the average values for each rule. The largest between-rule differences in average $\delta^{13}C$ measurements are about 0.5‰, which is somewhat larger than a realistic sample preparation and analysis error of *ca.* 0.2–0.3‰, but notably less than the range in average $\delta^{13}C$ over ten years for either marking rule (*e.g.* 3.1‰ in MB2001). Except for 2001, large differences reflect less negative (less depleted) average $\delta^{13}C$ in ST2009 than in MB2001. This direction of bias, observed in 25 of the 37 individual comparisons, is consistent with the false latewood band being included in latewood by the ST2009 rule, because the band is presumed to form in a period of water stress contributing to less negative $\delta^{13}C$.

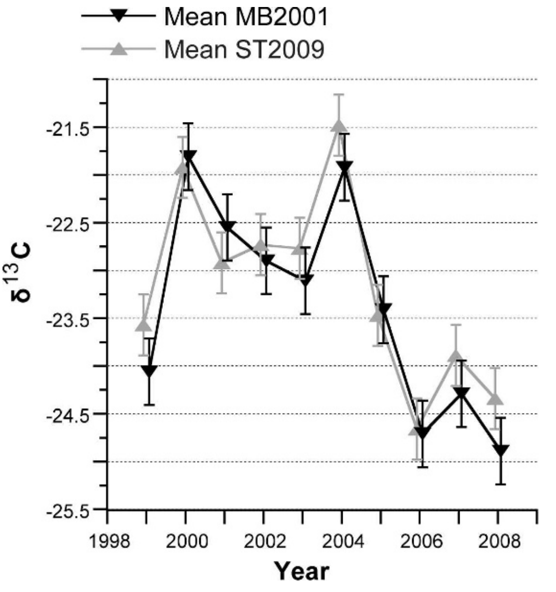

Figure 4. Time plot of $\delta^{13}C$ from latewood cellulose segmented by MB2001 (black) and ST2009 (gray) marking rules. Triangles represent mean $\delta^{13}C$ value from four trees per rule. Error bars calculated as ± 2 standard errors of the mean in each year.

LW Dependence on Antecedent EW

Adjustment of LW index for dependence on antecedent EW index defaulted to a linear model (no quadratic term) for 208 of the 306 cores analyzed at the four sites. Examples of linear and quadratic fits for two cores at site PRM are shown in Figure 5. The strong dependence of LW index on EW index for these particular cores is notable, as measured by regression R^2 exceeding 0.70. Core PDF19B (Figure 5A) happened to default to a linear model because the quadratic model (not shown) had a negative (though small) coefficient on the squared EW index. Core PDF16B (Figure 5B) is the best example of curvature in LW-

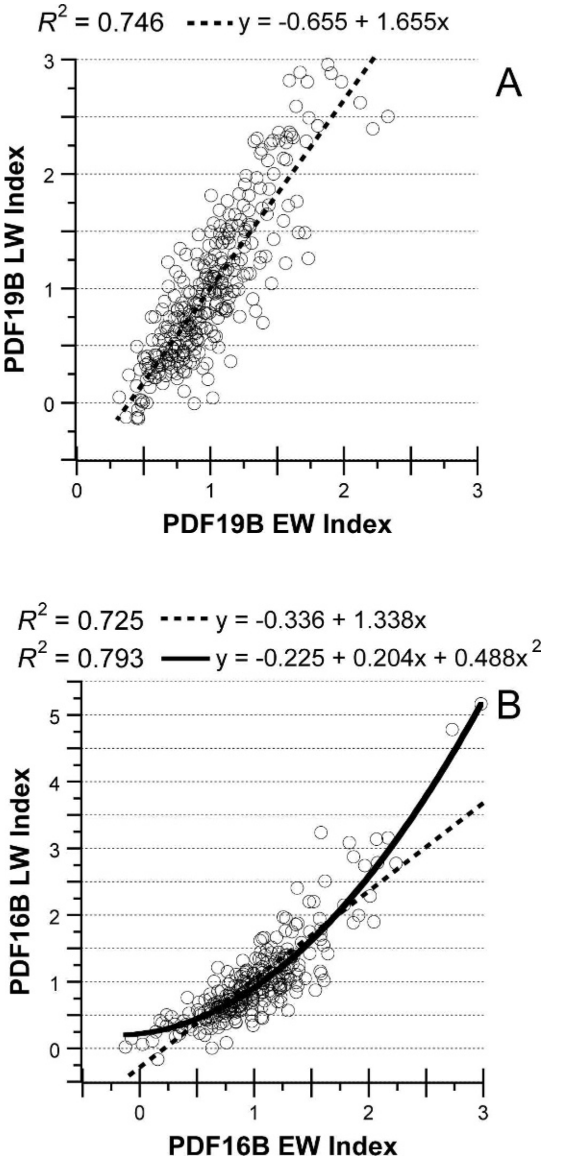

Figure 5. Scatter plots illustrating linear (A) and curvilinear (B) dependence of LW index on EW index for selected cores. Cores identified by axis labels. Regression model coefficients and R^2 annotated above.

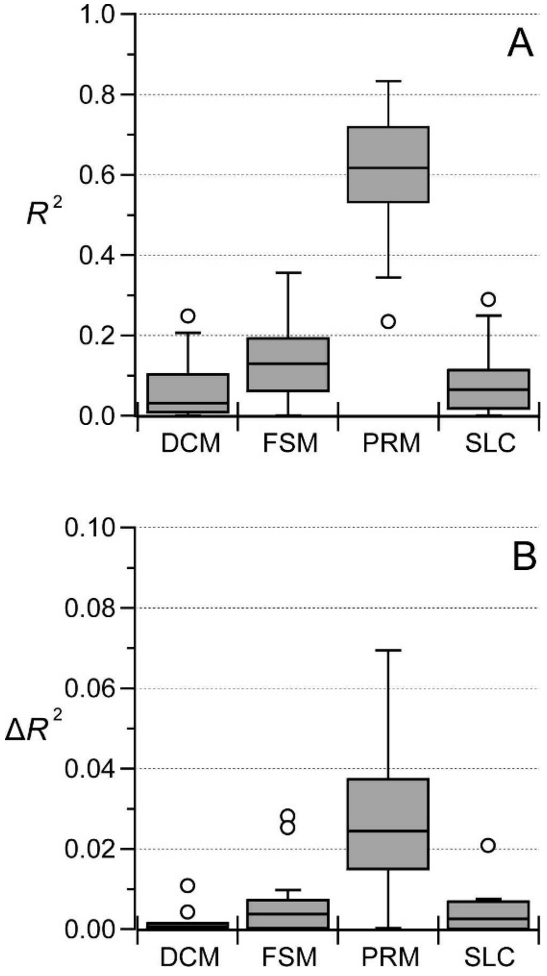

Figure 6. Boxplots summarizing dependence of LW index on EW index. (A) Distribution of R^2 from regression of LW index on EW index for cores from the tree-ring sites. Number of cores is 69 (DCM), 94 (FSM), 71 (PRM), and 72 (SLC). (B) Additional R^2 for those cores for which a quadratic term has entered the regression. Numbers of cores are 12 (DCM), 23 (FSM), 49 (PRM), and 14 (SLC).

EW relationship in our data, and even here the addition of the quadratic term adds just seven percent variance explained in regression over the corresponding linear model, marked by the dashed line.

Strength of the LW-EW relationship varies dramatically within and among the four sites, as illustrated by a boxplot summary of regression R^2 from the adjustment models of 306 cores (Figure 6A). For example, regression R^2 at DCM ranges from 0 to 0.25 while that of PRM varies from 0.24 to 0.83. PRM appears to differ greatly from the other sites, as indicated by the lack of overlap in the R^2 interquartile ranges (Figure 6A). Quadratic adjustment models generally yielded little gain in R^2 over linear models (ΔR^2; Figure 6B). The maximum gain for any core was $\Delta R^2 = 0.07$ at PRM; this extreme example is the

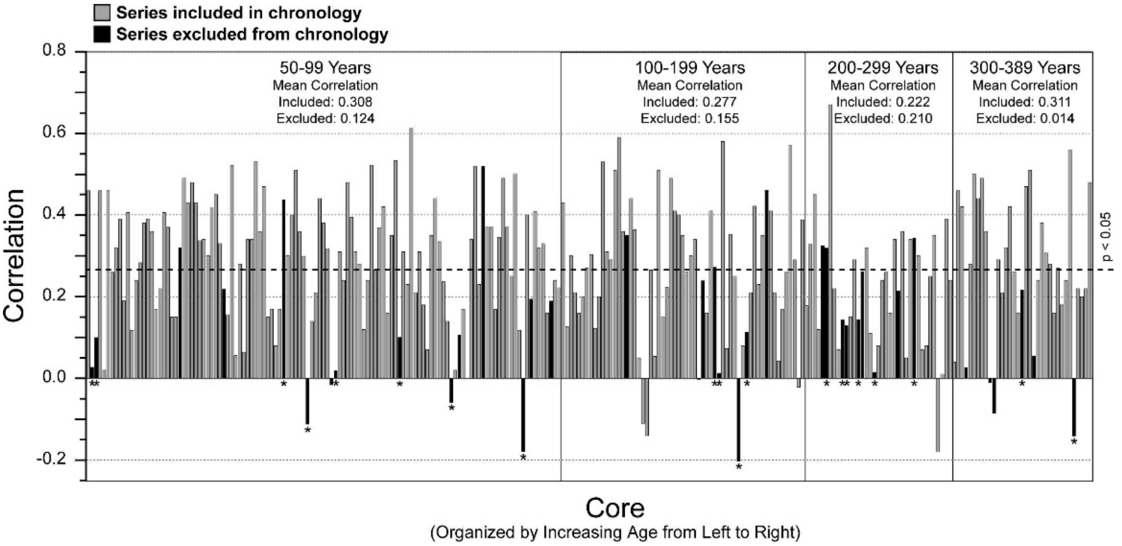

Figure 7. Correlation of July–August precipitation with LW_a index of all individual cores. Analysis period 1937–1986. Cores ordered left to right in order of increasing age and subdivided into age bins. Grey bars indicate series included in site chronologies. Black bars indicate series excluded from chronologies because of thin and little-varying LW. Asterisks indicate series excluded from site chronologies because of low correlation with site chronology, as determined through analysis with COFECHA (Holmes 1983). Analysis uses version of LW_a by MB2001 marking rule.

same core used previously in Figure 5B to illustrate curvature in the LW-EW relationship. Median ΔR^2 at the four sites was less than 0.01, corresponding to less than one percent additional variance explained by the quadratic adjustment model (Figure 6B). Again, PRM appears to differ from the other sites, with ΔR^2 interquartile ranges that do not overlap those from the other sites. The source of this strong seasonal autocorrelation is unknown, but possibly is related to site-specific environmental conditions such as substrate or subsurface hydrology.

Correlations of partial-width site chronologies with precipitation totals, 1896–2008, for their respective seasons are all statistically significant beyond the 99.9% confidence level (Table 3). Except for DCM, correlations are uniformly higher for the cool season than for summer. The highest correlation at any site is 0.73 for the cool season and 0.64 for summer.

The correlation of LW_a with summer precipitation appears to be relatively insensitive to whether the adjustment of LW for EW is done at the site-level or core-level: the maximum difference in correlation caused by this factor at any site is less than 0.02 (Table 3), and this difference is not consistent between sites. Despite the lack of evidence for stronger summer-moisture signal with adjustment at the core level, we conclude that this may be the preferred alternative in view of the occasionally large differences in strength of LW-EW relationship among cores. Adjustment at the core level retains the flexibility to evaluate the potential relationship between age and climate sensitivity, and to investigate possible differences in moisture signals related to particular patterns of LW dependence on EW.

Tree Age and Climate Sensitivity

Comparison of individual core LW_a index with July–August precipitation for the common period 1937–1986 indicates the strength of summer precipitation signal varies greatly among trees (Figure 7). For cores included in the site chronologies, no systematic relationship between tree age and sensitivity emerges and average climate correlation for each of the four age classes is quite similar. The series with segments excluded from the final chronologies because of low interseries correlation or below-zero detrending curves exhibit lower correlations, on average, with monsoon precipitation than those that were included in the chronologies (r = 0.144 and 0.280, respectively). Likewise, no clear age relationship emerges for the excluded individuals, although those excluded from the oldest age class exhibit a notably lower correlation than those included.

As described earlier in this paper and by all NAM tree-ring studies, LW becomes thin and potentially less variable with increasing biological tree age. This seems to be particularly problematic in over-aged or hyper-stressed trees, as was the case in the El Malpais study (Stahle *et al.* 2009). A caveat to our finding of no clear relationship between age and climate sensitivity is that the samples in our study are relatively young trees (less than 400 years) with relatively robust growth rates. In all cases, the tendency for loss of signal with age might be largely countered by excluding those time-series segments of precisely dated LW whose growth curves drop below some critical threshold or those that have markedly low correlation with the master chronology. As in all related studies, the authors advocate buffering against this potential challenge by including young to middle-aged trees in collections, effectively age-stratifying the chronologies progressively through time.

Climate Signal in the Partial-Width Chronologies

Correlation of adjusted-LW index with summer precipitation increases with averaging over sites (Table 3, last column). For the MB2001/site-level version of LW_a index, the highest correlation for individual sites is 0.636, whereas the correlation with the four-site average is 0.725. Correlation of EW index with cool-season precipitation also increases with averaging over sites, but to a lesser degree. The amplified effect for the summer season is probably caused by precipitation anomalies being more spatially heterogeneous with summer convective thunderstorms than with winter cyclones. The precipitation series used for the correlation analysis is a regional average, and anomalies in that series are probably more representative of the anomaly at a given location in winter than in summer. This phenomenon may also contribute to the generally lower correlations for LW_a index than for EW index with their respective seasonal precipitation.

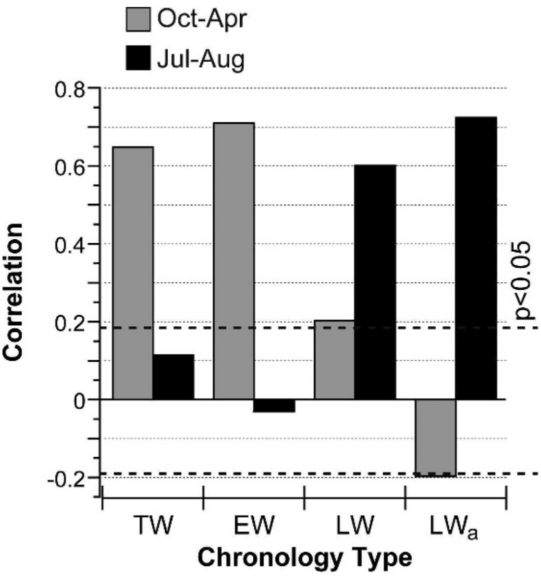

Figure 8. Coefficients for seasonal precipitation correlated with the regional average TW, EW, LW, and LW_a chronologies for the period 1896–2008. Partial-width components defined by MB2001 marking rule.

The contrasting seasonal-precipitation signals in the various partial-width and total-width components averaged over the four sites are summarized by the bar chart in Figure 8. A summer-precipitation signal is essentially absent in TW index, but is significant in indices of LW and LW_a. Adjustment of LW index for dependence on antecedent EW index raises the correlation with summer precipitation above 0.70, and shows that a simple linear regression model using LW_a averaged over just four sites could explain more than 50% of the variance of regionally-averaged summer precipitation. Considering the spatial heterogeneity of summer rainfall, this percentage could probably be increased with expanded site coverage.

The bar chart in Figure 8 also points to a spin-off benefit of partial-width measurement, namely improvement over TW in resolution of cool-season precipitation variations. The increased correlation with cool-season precipitation of EW index over TW index shown in Figure 8 amounts to roughly 5% more variance explained in a regression-based reconstruction model. Ability to separately reconstruct cool-season and warm-season precipitation signals will be useful for studying the phenomenon of conditional seasonal precipitation anti-correlation in the NAM region (see Stahle *et al.* 2009).

CONCLUSION

Partial-width measurements of *Pseudotsuga menziesii* have a statistically significant signal for both summer (from LW_a) and cool-season (from EW) precipitation in the NAM region. The warm-season signal is not available from TW measurements, and the cool-season signal is weaker in TW measurements. Properly developed LW_a chronologies can potentially explain more than 50% of the variance of summer (July + August) precipitation in the study area. This is an important result for future dendroclimatic studies of the NAM, a critical climatic component that influences environment and society in the US Southwest.

Summer-precipitation sensitivity in LW_a index is robust to the treatments considered here. Excluding the false latewood band from the LW measurements (MB2001) yielded a typically stronger but not significantly different signal for summer-precipitation than those LW measurements that included the false latewood band (ST2009). Likewise, the MB2001 and ST2009 $\delta^{13}C$ measurements were statistically indistinguishable, but the ST2009 measurements were less negative in 25 of 37 comparisons. In agreement with previous studies (Meko and Baisan 2001; Stahle *et al.* 2009) removal of the LW dependence on antecedent EW is crucial for extracting the summer-precipitation signal. Our results suggest that site-level LW adjustment (regressing site-level LW index chronology on the site-level EW index chronology) is adequate for these data. However, the strength of the EW-LW relationship varied widely between trees, supporting the argument for adjustment at the core level rather than the site level in chronology development. No strong advantage was found in a quadratic over a linear model for adjustment, but the obvious curvature in scatter plots of LW on EW for a few cores suggests that a flexible model allowing for curvature should also be considered in operational studies.

Dramatic tree-to-tree variations in the strength of summer-precipitation signal suggests that further research is needed to understand how physiographic micro-site, tree phenology, tree age, and other factors influence the tree-growth response to monsoon climate. Further investigations of the false rings' significance are currently being conducted by the authors, including weekly observations of cambial phenology and xylogenesis at the BEA site (Figure 2; Table 1), a reflected light investigation for potential climate signal in primary and secondary peaks of LW density, and the development of false-ring frequency chronologies with methods that are commonly used in studies of fire history.

Our results confirm earlier findings that advanced age may be associated with a loss or reduction in signal strength for summer moisture, but suggest that problematic cores can be effectively identified by weakening of correlation of ring-width patterns of individual trees with the common growth-pattern at the site. Stratification of middle-aged (*e.g.* 100 to 250 yr-old) trees throughout the length of a chronology is, however, an important consideration in field sampling and chronology development for summer-precipitation reconstruction from LW_a.

This study has focused on one tree species and a fairly limited geographical portion of the area of NAM influence. The study area was intentionally chosen because NAM-related precipitation is highly variable and a major portion of the annual total. More research is needed to determine if our findings can be generalized to other species and geographic and climatic settings in the Southwest. Tree-ring specimens used in this study will be permanently curated in the collection and archives of the Laboratory of Tree-Ring Research. Partial-width measurements prepared for this study will be made available through the International Tree-Ring Data Bank (ITRDB; ttp://www.ncdc.noaa.gov/paleo/treering.html).

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