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BRIDGING THE GAP WITH SUBFOSSIL DOUGLAS-FIR AT MESA VERDE, COLORADO

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ABSTRACT

Old Rocky Mountain Douglas-fir (*Pseudotsuga menziesii*) trees and remnant "subfossil" logs have been found on the outcrop of a mafic igneous intrusion above the Mancos River Valley near Mesa Verde National Park. These trees and logs have been used to develop earlywood (EW), latewood (LW), and total ring width (TRW) chronologies dating from AD 722–2011. The new chronologies include good series replication during the former chronological "gap" from AD 1250 to 1400, which was so problematic for the initial development of the "Central Pueblo" chronology by A. E. Douglass. Discrete reconstructions of the cool-season (September-May) and early warm-season (June-July) moisture balance for Mesa Verde have been derived from the EW and adjusted LW width chronologies from the Mancos Valley. Cool-season drought is estimated to have been more severe and sustained than early warm-season conditions during the "Great Drought" of the late-13th Century when southwestern Colorado was depopulated. The combined archaeological, subfossil, and living tree chronologies of EW, LW, and TRW for the Mancos River and Mesa Verde Douglas-fir now date from AD 480–2011.

Keywords: tree rings, *Pseudotsuga menziesii*, dendrochronology, archaeology, moisture deficit.

INTRODUCTION

The development of the master tree-ring chronology for the southwestern United States by A. E. Douglass (1929, 1935) using living trees and wood remains recovered from prehistoric and colonial era archaeological sites was one of the most significant intellectual achievements in the history of archaeology and dendrochronology (Webb 1983:145). The multi-year effort to bridge the chronological gap between the prehistoric and modern tree-ring records in particular involved locating wood and charcoal in archaeological sites of intermediate age, an effort guided largely by stratigraphic relationships and ceramic seriation (Douglass 1935; Robinson 1990). Eventually a single charred timber (HH-39) with a high-quality tree-ring record recovered from a late prehistoric Pueblo site at Show Low, Arizona, closed the gap between the living tree and archaeological sequences with certainty (Douglass 1935; Haury 1962). This chronology development effort, which involved several so-called "Beam Expeditions" to archaeological sites across the Colorado Plateau, was a collaboration between the archaeological and dendrochronological communities (Robinson 1990), and still stands as one of the crowning scientific contributions of dendrochronology, the most accurate and precise dating method in geochronology.

The chronological gap between the thousands of tree-ring series from prehistoric archaeological sites and the many thousand modern records from living trees, roughly the period from AD

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1270–1400, remains a period of very low specimen replication in most long Southwestern tree-ring chronologies. This is particularly true for some species and subregions such as Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] from Mesa Verde, Colorado (specifically *P. menziesii* var. *glauca*). The combined archaeological and modern tree-ring record of Douglas-fir for Mesa Verde National Park extends from AD 480–2008 (*e.g.* Stahle *et al.* in press), but the period from 1284–1380 is spanned by several radii from only a single tree, the so-called "Schulman old tree," discovered in a tributary of Navajo Canyon by Edmund Schulman in 1946 (Schulman 1947). In fact, the history of tree growth and climate at Mesa Verde during the Great Drought from 1276–1290 (Douglass 1929), which may have played a role in the depopulation of southwestern Colorado in the late 13th Century (Douglass 1935; Kohler 2010), is based largely on the tree growth record of just Schulman's old tree. There is no doubt about the validity of the tree-ring chronology during the late 13th Century, of course, nor about the reality of severe sustained drought across the Colorado Plateau during the same time period because both the chronology and climate conditions have been substantiated by subsequent research (*e.g.* Douglass 1936; Schulman 1947; Smiley *et al.* 1953; Fritts *et al.* 1965; Grissino-Mayer 1995; Dean and Funkhauser 1996; Stahle *et al.* 2009). Nonetheless, the true severity and persistence of extreme drought over the Mesa Verde sector during the late 13th and 14th Centuries remains poorly documented in the available moisture-sensitive tree-ring record from this interesting archaeological district. This is especially true for Douglas-fir, which can provide valuable estimates of both cool-season and warm-season moisture conditions (Stahle *et al.* 2009; Griffin *et al.* 2012) relevant to the reconstruction of prehistoric agricultural productivity (Burns 1983; Van West 1994; Kohler 2010; Bocinsky and Kohler 2014).

Had Douglass realized the great longevity achieved by some Southwestern conifers on select microsites, or the availability of relict wood of great antiquity in some fire-protected landscape positions, it is possible that the Beam Expeditions might have been cut short in favor of the centuries-long time series of growth present in these select old trees and subfossil logs. We now realize that many of the most ancient living trees are found on magnesium-rich soils weathered especially from basalt and dolomite. Magnesium (Mg) is the central atom of the chlorophyll molecule and it activates light reactions during photosynthesis (Levitt 1954; Berg *et al.* 2002). Magnesium is also involved in many reactions involving enzymes and with the uptake and transport of phosphorus. Soils enriched in Mg appear to allow for efficient photosynthesis even when other essential growth factors are limited, thereby promoting growth and longevity under adverse conditions. Exceptional examples of ancient trees found on magnesium-rich substrates include bristlecone pine (*Pinus longaeva*) in the White Mountains, California, alerce (*Fitzroya cupressoides*) at Alerce Andino National Park in Chile, northern white cedar (*Thuja occidentalis*) on the Niagara Escarpment in Canada and the northeastern U.S., Douglas-fir at El Malpais National Monument, New Mexico, Montezuma baldcypress (*Taxodium mucronatum*) at Barranca de Amealco, Queretaro, and Siberian pine (*P. sibirica*) on Mongolian lava fields (Schulman 1958; Larson and Kelly 1991; Lara and Villalba 1993; Grissino-Mayer 1995; Stahle *et al.* 2011; Pederson *et al.* 2014). Schulman also discovered very old Rocky Mountain Douglas-fir on a dolomite slope near Eagle, Colorado (the oldest prior to the discovery of the old trees at El Malpais; Schulman 1956). These magnesium-rich substrates are one component of the predictive models used in the worldwide search for the environments that promote the longevity and survival potential of the most ancient trees.

The surficial geology of Mesa Verde is composed largely of Cretaceous sedimentary rocks, but small mafic intrusions with magnesium- and potassium-rich igneous petrology are present in the National Park, in the Mancos River valley on the west slope of Weber Mountain, and just south of the National Park on Ute Reservation lands (Figure 1). We sampled living Douglas-fir trees and subfossil wood on the Mancos Valley igneous intrusion during a survey of old growth woodlands in and near Mesa Verde National Park. The Mancos Valley igneous outcrop only covers some

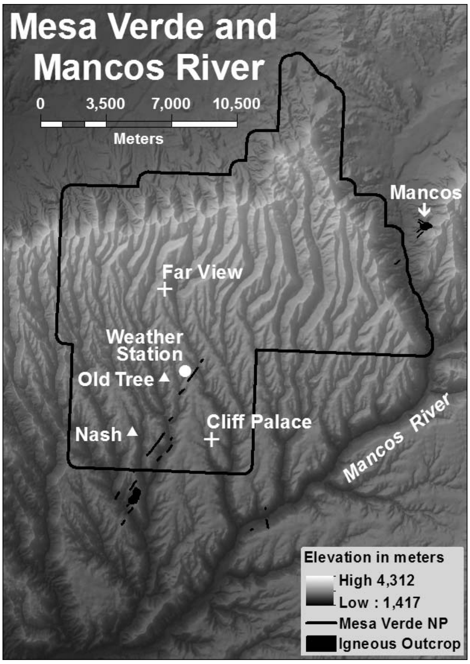

Figure 1. The terrain of the Mancos River and Mesa Verde area is illustrated along with the igneous outcroppings as mapped by the National Park Service (black polygons; NPS 2006). The Mancos River Douglas-fir site is located on the north-facing slopes of the igneous outcrop just east of the Park boundary. Select archaeological sites, tree-ring collection sites, and the weather recording station at National Park headquarters are also indicated. DEM datasets for the entire state of Colorado can be accessed at: http://coloradoview.org/cwis438/websites/ColoradoView/Data.php?WebSiteID=15

20 ha and is sparsely vegetated with mixed conifers (pinyon-juniper and Douglas-fir). The Douglas-fir are located exclusively on protected north-facing microenvironments, and include very old living trees, recently dead trees, and remnant subfossil wood thinly scattered below a cliff face on the rocky talus slope (Figures 2 and 3).

This report describes the development of 1290-year-long chronologies of earlywood (EW), latewood (LW), and total ring width (TRW) from the living trees and subfossil wood at the Mancos Valley igneous outcrop. These new chronologies are used to develop discrete reconstructions of the cool-season and early warm-season moisture balance for the Mesa Verde sector. The decadal droughts of the Anasazi era are examined on a seasonal basis in these new reconstructions. The longest high quality EW, LW, and TRW data of

Figure 2. This view west from the igneous outcrop (foreground) above the Mancos River, Colorado, illustrates some of the recent mortality within the Douglas-fir stand. The northern end of Mesa Verde is located on the horizon (left).

Douglas-fir from Mancos River and various modern and archaeological collections from Mesa Verde itself are then compiled into well replicated regional chronologies dating from AD 480–2011.

SITE LOCATION

The terrain of southwestern Colorado in the vicinity of Mesa Verde and the Mancos River is

Figure 3. Subfossil Douglas-fir logs are present in various states of decomposition on the rocky talus slopes below the igneous outcrop near the Mancos River, Colorado. The log in the foreground (MAN82) dates from AD 906 (pith) to ±1618, with a ring count after 1580 to the eroded outer edge of the specimen (no sapwood present). The log in the background (MAN80) dates from AD 1345 (pith) to ±1845, with a ring count after 1750. Sapwood is present on MAN80 and the 1845 date is the probable death date of the tree. Preservation has therefore been exceptionally good for over 165 years.

illustrated in Figure 1. Only two small igneous outcrops and a few narrow igneous dikes have been mapped within this district. The Mancos Valley outcrop extends from 2070 to 2245 m a.s.l. and includes some 5 ha of north-facing terrain with a highly drought stressed population of Douglas-fir. Satellite images of the Ute Reservation outcrop suggest that mixed conifer woodland is only sparsely present and the elevation and exposure do not seem favorable for the presence of Douglas-fir, but we have not visited this location.

Douglas-fir trees are present near the summit of the igneous outcrop (Figure 2) and down the north-facing slope into a small upland drainage. There is an escarpment on the north edge of the outcrop and ancient Douglas-fir grow isolated in highly precarious positions along the cliff edge. All age classes of Douglas-fir appear to be present including juvenile, mature, senescent, standing dead trees, fallen logs, and remnant wood. Considerable mortality appears to have occurred among the Douglas-fir during the ongoing drought of the early 21st Century, based on the presence of many recently dead trees (Figure 2), although we did not specifically date mortality in this stand. Some dead trees have fallen onto the talus slope below the cliff and are still present on a scattered basis preserved from fire and excessive moisture on the barren rock talus (Figure 3). A few remnant logs were partially buried in the talus and it seems possible that older wood fragments might be partially preserved beneath the surface.

DATA AND METHODS

Instrumental Climate Data

The instrumental climate data used in these analyses were obtained from the PRISM grid point located at 37.2°N, 108.5°W, and 2139 m a.s.l. (Daly *et al.* 2002), which is the closest point to the weather station at National Park headquarters on Chapin Mesa where daily observations were started in 1922 (Figure 1; headquarters station = NOAA station ID 055531, Western Regional Climate Center, Desert Research Institute). The PRISM monthly grid point estimates are based on all available weather stations in the Four Corners region. The PRISM grid point data at headquarters were used in this analysis after 1923 because they are very highly correlated with monthly and seasonal values from the headquarters weather station (Stahle *et al.* in press), and they do not have missing monthly values. Both records are representative of the mesa-top environment of Mesa Verde itself, and the new EW, LW, and TRW chronologies from the Mancos River site are very highly correlated with select monthly values in both datasets.

Tree-Ring Data

Multiple cores were extracted from 28 living trees, and cross-sections were cut from 13 subfossil logs at the Mancos River site, all Douglas-fir (Table 1). The specimens were prepared, crossdated visually under the microscope with the aid of skeleton plots, and measured with a precision of 0.001 mm. The discrimination between EW and LW width was measured optically using the procedures outlined in Schulman (1942, 1952) and Stahle *et al.* (2009). The quality of the dating and measurements for each of the EW, LW and TRW data sets was then evaluated with the computer program COFECHA (Holmes 1983).

For this analysis, signal-free standardization was used to detrend each measured tree-ring time series (Cook *et al.* 2014; Melvin and Briffa 2008). This detrending approach is designed to preserve high- and medium-frequency variance (*i.e.* less than the mean length of the component series). Signal-free standardization also helps avoid backward propagating distortion of the growth trend fit to the time series resulting from a large common growth signal towards the end of the sample time series, arising, for example, from the global warming signal in many boreal conifers (Melvin and Briffa 2008) or from the recent early 21st Century drought across the Colorado Plateau, which has negatively impacted Douglas-fir growth in the Mesa Verde sector. An age-dependent spline was used to start the detrending procedure, indices were calculated as residuals from the fitted growth curve, adaptive power transformations were applied to the residual time series, and the indices were computed using the Tukey robust biweight mean (Cook *et al.* 2014).

Table 1. Dated trees and logs recovered from the igneous outcrop at Mancos River, Colorado. The specimen identification, inner and outermost dated rings are listed, along with specimen type, and minimum tree age (not allowing for missing rings to pith or rings lost to erosion).

ID	Inner		Outer		Living	Relict	Age
MAN08	1654		2010		X		357
MAN09	1462	np	2010	±	X		549
MAN10	1502	±np	2010	±	X		509
MAN11	1829	np	2010		X		182
MAN12	1632	np	2010		X		379
MAN13	1746		2010	±	X		265
MAN14	1787		2010		X		224
MAN16	1850	np	2010		X		162
MAN18	1953	p	2010		X		58
MAN19	1965	p	2010		X		46
MAN20	1649		1777			X	129
MAN51	1720	p	2011		X		292
MAN52	1682		2011		X		330
MAN53	1911	np	2011		X		101
MAN54	1867	p	2011		X		145
MAN55	1747	np	2011		X		265
MAN56	1744		2011		X		268
MAN57	1696		2011		X		316
MAN58	1828		2011		X		184
MAN59	1911	np	2011		X		101
MAN60	1841	p	2011		X		171
MAN61	1623		2011		X		389
MAN62	1599		2011		X		413
MAN63	1869	p	2011		X		143
MAN64	1596	np	2011		X		416
MAN65	1818	p	2011		X		194
MAN66	1595	p	2011		X		417
MAN67	1916	p	2011		X		96
MAN68	1886	np	2011		X		126
MAN70	1948	np	2011		X		64
MAN72	1861	p	1955			X	95
MAN73	1844	p	1942			X	99
MAN74	1765		1939			X	175
MAN80	1345	p	1845	±		X	501
MAN81	940	±p	1580	±		X	641
MAN82	906	np	1618	±		X	713
MAN83	996	p	1511			X	516
MAN84	721	fp	1418	±		X	698
MAN85	1493	p	1963	±		X	471
MAN86	1148	p	1644	±		X	497
MAN87	1156	p	1494	±		X	339

Symbols: ± = ring count involved; p = pith; np = near pith; fp = far from pith.

The derived EW and LW chronologies at Mancos River are very highly correlated (r = 0.84; 722–2011). The so-called adjusted latewood chronology (LW_{adj}) was therefore computed to remove the dependency of LW width on EW in order to provide a discrete estimate of warm-season climate conditions not influenced by preceding climate or the physiological persistence of growth within the annual increment (Meko and Baisan 2001; Stahle *et al.* 2009). The LW width chronology was regressed on the EW width chronology using robust regression to discount outliers. The default robust regression procedure available in the Modern Applied Statistics with S package for the statistical language R (MASS package; Venables and Ripley 2002) was used, where the model fit uses iterated re-weighted least squares and large residuals are down-weighted. The residuals were normalized by subtracting the median and dividing by the inter-quartile range. The median and interquartile range from the original LW chronology was then restored to the residuals and a constant of 1.0 was added to eliminate negative values. For computation of the adjusted LW chronology only, the EW and LW chronologies were first computed using option 2 in ARSTAN (Cook and Krusic 2005; negative exponential or straight line with zero or negative slope, using standard chronologies in both cases), to avoid unrealistic low-frequency variance in the derived LW_{adj} chronology (when calculated with signal-free methods) associated with the surge in recruitment after the 16th Century megadrought (Figure 4). All other chronologies reported here were computed with the signal-free method.

Reconstruction Methods

Correlation analysis was then used to separately model the EW and LW_{adj} response to monthly temperature and precipitation, and to identify the optimal seasons for climate reconstruction with each subannual chronology. An effective moisture index was computed for the headquarters station as the difference between total monthly precipitation and potential evapotranspiration, or P-PE. Potential evapotranspiration was computed from monthly mean temperature using the Thornthwaite method (Thornthwaite 1948; Burnette and Stahle 2013; monthly mean temperature was computed from minimum and maximum temperature available at the PRISM grid point). The monthly P-PE estimates were transformed into anomalies by subtracting the mean P-PE for the 1922–2011 period of record. Positive P-PE values represent wet and cool conditions, and negative values are dry and warm. This P-PE index does not include any prescribed month-to-month persistence to model soil moisture storage and was used to reconstruct restricted seasonal moisture variables from EW and LW_{adj} chronologies.

To develop the reconstructions, the tree-ring chronologies and two lead and lagged versions were entered into forward stepwise regression as potential predictors of September-May P-PE for EW and June-July P-PE for LW_{adj}. Autoregression in the predictor and predictand time series during the calibration period (1969–2011) was identified using the corrected Aikaike Information Criteria (AICc; Cook *et al.* 1999), and persistence in both time series was removed prior to calibration. Independent climate data available for the same station prior to the calibration period were used to test the derived reconstructions, and the Pearson correlation (r), reduction of error (RE), and coefficient of efficiency (CE) statistics were used to measure the degree of fit between observed and reconstructed values (Cook *et al.* 1999).

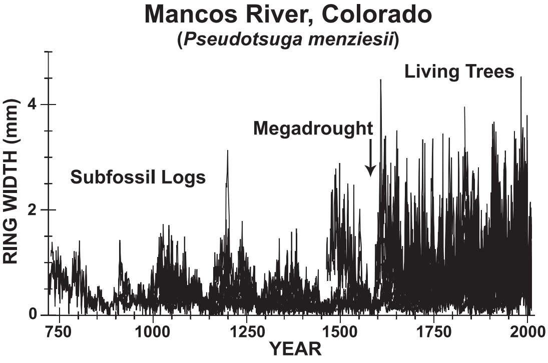

Figure 4. The total ring width measurements for all dated Douglas-fir trees and subfossil logs are plotted from AD 722–2011 (92 radii total). Note the suppression of growth during the severe sustained droughts of the mid-12th, late-13th, and late-16th Centuries. The difference in average growth rates between the subfossil logs and the living trees may largely reflect microsite conditions.

RESULTS

The Mancos River chronologies of EW, LW, and TRW are all based on 92 radii from 28 living trees, 13 subfossil logs, and date from AD 722–2011 (Figures 4 and 5). The longest individual series have 698 and 713 dated annual rings and were derived from subfossil logs found on the talus slope below the cliff face (MAN84 was dated from AD 721 to 1381, and ring counted to 1418; MAN82 was dated from AD 906 to 1580, and ring counted to 1618; Table 1). MAN84 is a weathered specimen that does not retain sapwood or the innermost rings (an estimated 7 cm of radial growth is missing at

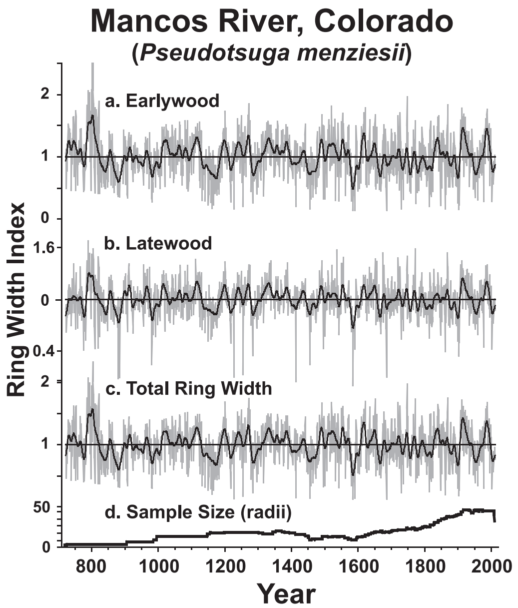

Figure 5. Mean index tree-ring chronologies of EW (a), LW (b), and TRW (c) computed with the Signal Free program (Melvin and Briffa 2008; Cook *et al.* 2014) for the Douglas-fir trees and logs from the Mancos River site. Decadal versions computed with a smoothing spline (Cook and Peters 1981; same in Figures 8, 9, and 10). The sample size changes over time are also plotted (d).

the center of the specimen). It is therefore likely that MAN84 was over 800-years old when it died, perhaps 850, and would therefore have been one of the oldest Rocky Mountain Douglas-fir individuals yet documented with dendrochronology (Brown 1996). The exceptional preservation of ancient wood on the talus at the Mancos River site is illustrated with specimen number MAN80 (1345p to ±1845), which retains pith, sapwood, and probably the final ring produced before tree death in 1845 or 1846 (Figure 3). Several other individual trees and well-preserved logs from the Mancos River outcrop are in the 500-year age class (Table 1). However, we did not sample the stunted trees in the most precarious positions among the cliffs, some of which appear to be exceptionally old.

As has been noted previously in other forest stands on the Colorado Plateau (T. P. Harlan, personal communication; Swetnam *et al.* 1999), the 16th Century megadrought and other severe sustained droughts appear to have impacted the demographic structure of the Mancos River Douglas-fir stand (Figure 4). Most living trees present on the site germinated after AD 1590. Our sampling of the living trees was not randomized, but only two germinated before 1550 (Table 1). Both of these individuals exhibited the external characteristics of ancient trees (Schulman 1954; Stahle 1997), and very few living trees in that most senescent cohort appear to still be present in the stand.

The ring width data are plotted in Figure 4 for all 92 dated radii. Growth decline during some of the most intense droughts of the past millennium is apparent in these raw data, including the mid-12th, late-13th, and late-16th Century droughts. The elevated growth rates after 1590 (Figure 4) probably reflect a bias in the sampling of living trees and subfossil logs. Most of the old subfossil logs likely fell from the cliff edge, a more adverse microsite than the north facing slopes and ravine where most of the living trees were collected. This difference in mean growth rates between the living trees and subfossil logs, particularly the surge in growth rates following the 16th Century megadrought, complicated the chronology development process, including the derivation of realistic adjusted latewood estimates. However, the ring width time series from the living trees and subfossil logs are very highly correlated where they overlap in time and apart from the differences in growth rate appear to represent a homogenous sample from a single dendroclimatic population.

Mesa Verde with its Douglas-fir is widely considered to be the type site for tree-ring dating (Douglass 1939; Schulman 1946), with some of the strongest crossdating ever observed (M. A. Stokes, personal communication, 1973). The Mancos River stand is equally outstanding. None of the 50-year segments of EW or TRW tested in COFECHA were flagged for low correlation or possible dating error (984 total segments). Several 50-year segments in the LW data were flagged, but these were all associated with senescence and a consequent lack of inter-annual variability in some LW series and did not arise from mistakes in dating or measurement. The average correlation among all possible series (RBAR, Cook and Pederson 2012) is 0.69, 0.41, and 0.68 for the detrended and prewhitened EW, LW, and TRW data, respectively.

Only 1.24% of the rings were missing in this Mancos River sample (*i.e.* 304 out of 24,493 dated and measured rings were missing). The worst single year for missing rings was 2002, during one of the most extreme droughts in the instrumental record for Colorado (Pielke *et al.* 2005) when 41 out of 50 dated radii exhibited no anatomical evidence for cell growth (82% missing rings). This extraordinary drought required sampling of young trees from the most mesic positions within this otherwise very arid site in order to fully document the chronology of annual ring widths. The second worst year occurred in 1413 when 13 of 17 dated radii lacked evidence for cell growth on the available specimens (76% missing). Before AD 907 the Mancos chronology is based on only three radii from one subfossil log (MAM84), and in 880 and 884 two of three radii lacked evidence for radial growth (67% missing). Nonetheless, the early dating of the Mancos River chronology from 721 to 906 fully obeys the regional tree-ring dating chronology for the Colorado Plateau first defined by A. E. Douglass.

The mean index chronologies computed with the signal-free method (Cook *et al.* 2014; Melvin and Briffa 2008) are plotted in Figure 5 along with the sample size trace from AD 722–2011. The sample size falls to just three radii from one tree before AD 907 (only two radii before 727), but during the 1270–1400 chronological "gap" following abandonment of the Mesa Verde area by ancestral Pueblo it does not fall below 17 radii from eight trees for EW or TRW, and not below 15 radii from eight trees for LW (a few senescent and weakly correlated LW segments were removed from this interval). The moisture history of the Colorado Plateau for the past 1290 years is clearly represented in these Mancos River ring width chronologies, including the profound and prolonged droughts of the mid-12th, late-13th, and late-16th Centuries. The favorable growth and inferred wetness of the early and late 20th Century is also unusual compared with the well-replicated portion of the chronology after AD 1000 (Figure 5).

The three chronologies in Figure 5 are highly cross-correlated (r = 0.84, 0.99, and 0.89 for EW vs LW, EW vs TRW, and LW vs TRW, respectively). The adjusted latewood chronology was therefore computed in an effort to derive warm-season climate estimates not heavily influence by the preceding winter-spring climate conditions that drive EW growth. The EW chronology is positively correlated ($p < 0.05$) with monthly precipitation totals at the headquarters station on Mesa Verde from September through May (1925–2011) and significantly negatively correlated with monthly mean maximum temperature from May-July (not shown). The LW_{adj} chronology is correlated with monthly precipitation totals and maximum temperatures in June and July.

To represent the positive response to precipitation and the negative response to temperature in both the EW and LW_{adj} chronologies, monthly moisture balance indices (P-PE) were computed for the PRISM point closest to National Park headquarters. No month-to-month persistence term was included so that the warm season P-PE could be estimated without dependence on prior conditions. The correlation between monthly P-PE estimates at Mesa Verde and the EW and LW_{adj} chronologies from Mancos River are plotted in Figure 6. These results indicate that the EW chronology is primarily correlated with the moisture balance during the fall, winter, and spring months prior to the formation of EW, similar to the response of TRW at Mesa Verde noted by Schulman (1946) and Fritts *et al.* (1965). The cool-season climate response has been reduced for the LW_{adj} chronology, which is most strongly correlated with the June-July moisture balance (Figure 6). Although the EW and LW_{adj} chronologies still share some response to the cool season, the two reconstructions of cool- and warm-season P-PE are uncorrelated over the past millennium (Figure 8).

The observed and reconstructed cool- and warm-season P-PE time series are illustrated in Figure 7 and the calibration and verification statistics are presented in Table 2. The EW chronology represents approximately 68% of the variance in the instrumental September-May P-PE data during the calibration period (1969–2011) and remains well correlated with the instrumental data during the verification interval (1925–1968). The LW_{adj} chronology explains 42% of the variance in instrumental June-July P-PE and is also well validated against independent instrumental observations from 1925–1968 (Table 2).

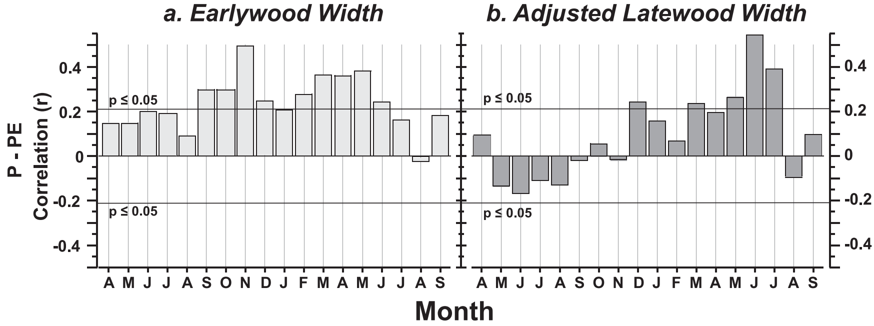

Figure 6. Correlation coefficients calculated for the period AD 1925–2011 between the monthly moisture balance (P-PE) at the Headquarters weather station, Mesa Verde National Park, and the earlywood (a, gray) and adjusted latewood width chronology (b, dark gray) from Mancos River, Colorado. In both cases the dendroclimatic year begins in April of the year prior to growth and extends through September of the year when these subannual ring components were formed. For the adjusted latewood chronology, note the reduction of correlation with P-PE during the preceding cool season compared with EW and the emergence of a strong current summer signal.

The cool-season moisture balance reconstruction from EW width at Mancos River extends from AD 722–2011, but the early warm-season moisture reconstruction based on LW_{adj} was censored prior to AD 1030 because of unrealistic values in the poorly replicated portion of the LW_{adj} chronology (Figure 8). These two seasonal moisture reconstructions are not correlated and in fact estimate very different conditions during certain episodes over the past 1,000 years. Most notably for the prehistoric occupations in the Mesa Verde region, the cool-season droughts of the mid-12th and late-13th Centuries were more severe and sustained than are now estimated for the early warm-season based on the Mancos River chronologies (Figures 8a *vs* 8b). A previous estimate of early warm-season moisture based on LW_{adj} data from Mesa Verde National Park (Stahle *et al.* in press), which was represented only by Schulman's old tree during the late 13th Century, indicated deeper and more persistent July drought during the 13th Century than is now suggested by the better-replicated LW_{adj} chronology from Mancos River.

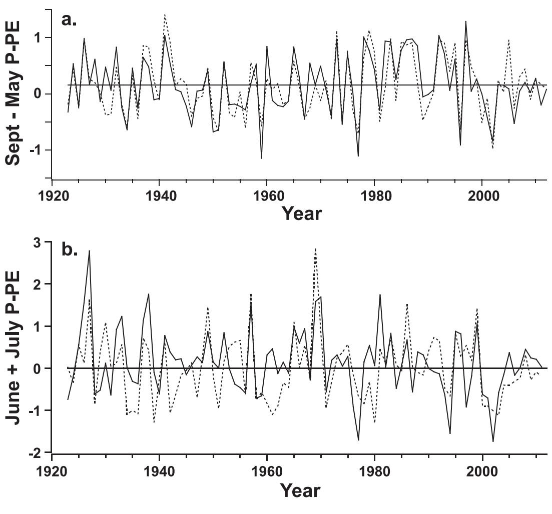

Figure 7. Observed (dashed line) and reconstructed (solid line) P-PE is plotted for the cool (a, September to May) and warm seasons at Mesa Verde (b, June and July). The statistics for the calibration and verification of the reconstructions for both seasons are reported in Table 2.

Other major differences between the cool-season and early warm-season reconstructions include (1) persistent cool-season drought in the 1460s when summer conditions were mostly wet, (2) persistent warm-season drought during the 1840s when wet conditions prevailed during the cool season, and (3) the prolonged cool season pluvials of the early and late 20th Century were not matched by exceptionally wet conditions during June and July (Figure 8). Decadal drought in the warm season is also estimated to have been more severe and sustained than cool-season dryness during the early and mid-13th Century at Mesa Verde (Figure 8).

The new EW, LW, and TRW chronologies from Mancos River add to the Douglas-fir tree-ring data already available from Mesa Verde. The four principal sources of subannual and annual ring width data for the Mesa Verde sector are

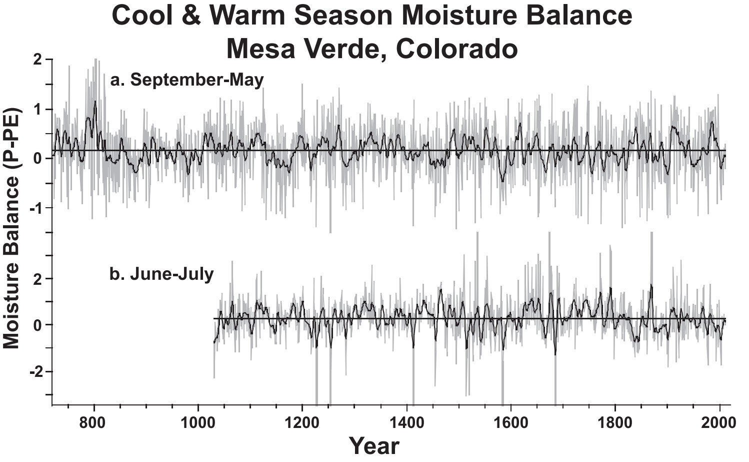

Figure 8. The EW width chronology was used to reconstruct the cool season moisture balance (P-PE average for September-May) from AD 722–2011 (a), and the adjusted LW chronology was used to reconstruct the early warm-season moisture balance (June-July P-PE) from AD 1030–2011 (b). These two reconstructions are not well correlated at the annual or decadal scale [$r = 0.079$ for the annual values (gray) and $r = 0.25$ for the 10-year smoothed versions (black) from 1030–2011] and in fact indicate strongly out-of-phase decadal moisture anomalies during the 1460s, 1840s, and 1990s.

illustrated in Figure 9 (total ring width only). The "best" Douglas-fir collections obtained from Mesa Verde archaeological sites by A. E. Douglass, *i.e.* Gila Pueblo, and other investigators were re-measured for EW, LW, and TRW by Stahle *et al.* (in press) and date from AD 480–1270 (Figure 9a). Three radii each for six Douglas-fir trees collected by E. Schulman, including the "old tree" were also re-measured (Figure 9b), and a recent collection of living Douglas-fir from Mesa Verde National Park by S. Nash was dated and measured for EW, LW, and TRW by R. D. Griffin (2013; Figure 9c). The new TRW chronology developed from the Mancos River site is plotted in Figure 9d.

The EW, LW, and TRW chronologies from these four collections are highly correlated during the various common intervals (*e.g.* Figure 9) and were therefore merged into regional Douglas-fir chronologies for the Mesa Verde-Mancos River

Table 2. Calibration and verification statistics computed for the reconstruction of the cool (September-May) and early-summer (June-July) moisture balance (P-PE) at Mesa Verde, Colorado (PRISM data used for the Headquarters location). The calibration interval is listed first (*e.g.* AD 1969–2011), followed by the verification interval (*e.g.* 1925–1968) for each reconstruction. The coefficients of the regression models, the variance explained (R^2_{adj} = coefficient of determination adjusted downward for the loss of degrees of freedom), the standard error of the estimates (SE), and the Durbin-Watson statistic (DW) are listed for each reconstruction. Bivariate models were selected for both seasons, using only tree growth during year (t) concurrent with the end of the instrumental climate season. The Pearson correlation coefficient comparing reconstructed with instrumental P-PE data during the statistically independent verification periods are shown for the reconstructions, along with the reduction of error (RE) and coefficient of efficiency (CE) statistics calculated on observed and reconstructed data in the verification period. All tests indicate successful verification.

	Coefficients							
Time Period	b_0	b_1	R^2_{adj}	SE	DW	r	RE	CE
September–May								
1969–2011	0.004	1.45	0.68	0.32	2.03			
1925–1968						0.79	0.65	0.62
June–July								
1969–2011	0.001	2.68	0.42	0.59	1.84			
1925–1968						0.67	0.41	0.40

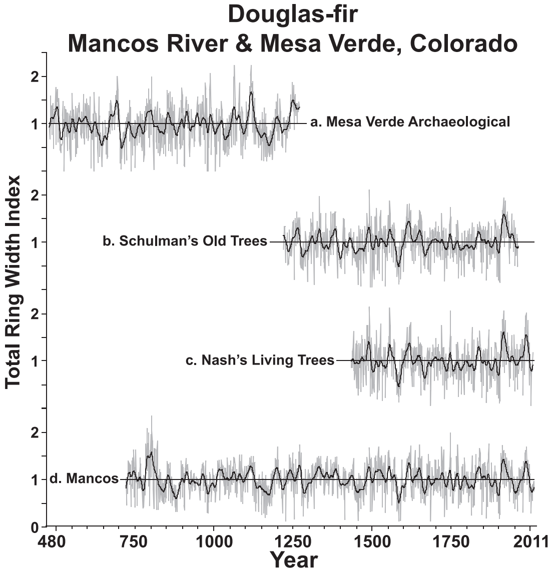

Figure 9. Mean ring width index chronologies for four selected collections of Douglas-fir from the Mesa Verde region of southwestern Colorado. Each chronology was computed with the Signal Free program (Melvin and Briffa 2008; Cook *et al.* 2014). The new data from the Mancos River provide a well-replicated link between the archaeological and living Douglas-fir collections from the region. The correlations between these various overlapping pairs of TRW chronologies are: r = 0.71 (722–1270), 0.79 (1220–1962), 0.85 (1434–2008), 0.39 (1220–1270), and 0.92 (1434–1962) for Mancos vs. MV archaeo, Mancos vs. Old Tree, Mancos vs. Nash, Old Tree vs. MV archaeo, and Old Tree vs. Nash, respectively.

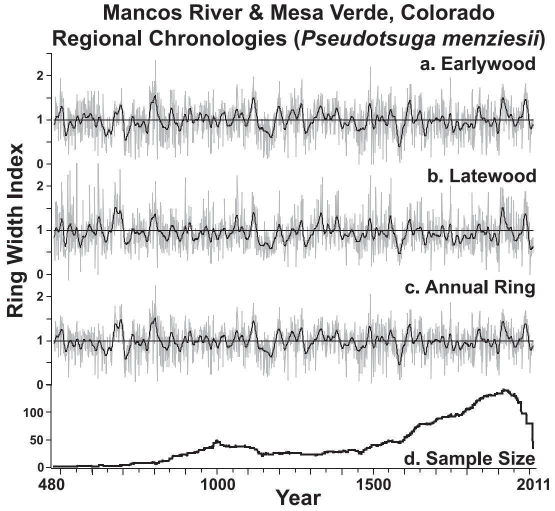

Figure 10. Mean index chronologies of EW (a), LW (b), and TRW (c) computed using the four collections of Douglas-fir from the Mesa Verde area of southwestern Colorado (the archaeological specimens, Schulman's old trees, Nash's living trees, and the Mancos River igneous outcrop, each illustrated in Figure 9). Sample size (d) falls to a few as just two radii before AD 623, and just a single radius from 546 to 553. From AD 1251 to 1400 sample size is not lower than 22 radii.

sector, all dating from AD 480–2011 (Figure 10abc). The sample size trace for these regional chronologies is also illustrated (for EW and TRW, and LW is only slightly lower at times; Figure 10d). Sample size does decline in the period from AD 1270–1400, but the gap between these regional chronologies originally filled by Schulman's single old tree is now much better replicated (21 radii from nine trees).

CONCLUSIONS

The new Douglas-fir chronologies of EW, LW, and TRW for Mancos River provide an interesting perspective on cool- and warm-season moisture variability over southwestern Colorado for the past millennium. Most significantly perhaps, the new moisture balance reconstructions suggest that the Great Drought of the late 13th Century was most severe and sustained during the cool season. The early warm-season moisture balance is estimated to have been average to above average for most of the late 13th Century, with the exception of the extreme dryness in AD 1283 and 1284, and the five-year episode of below-average conditions from 1281 to 1285 (Figure 8b). This is in sharp contrast with a previous estimate of the May-June moisture balance using adjusted LW width data from Mesa Verde itself, which was based entirely on Schulman's single old tree in the late 13th Century (Stahle *et al.* in press). The new LW width data from Mancos River do not support such profoundly dry early summer conditions during the era of Ancestral Pueblo depopulation of southwestern Colorado, and underscore the value of subfossil wood for chronology replication and extension.

The intuitive predictive modeling used to identify where in the modern human-altered landscape the most ancient living trees and remnant "subfossil" wood can still be located has progressed since the advent of dendrochronology in the early 20th Century. In one of his most interesting and important articles, Schulman (1954) made the famous association between great age in trees and harsh site conditions, particularly the widespread moisture stress at arid sites in western North America. But Schulman also described the association between over-age conifers and specific geological substrates (*i.e.* limestone; Schulman 1954). The apparent link between ancient tree growth and magnesium rich soils has since been identified at a number of sites worldwide where some of the oldest-known trees of several species have been discovered.

The persistence of relic wood on the landscape was also important to the development of the long bristlecone pine chronology in the White Mountains of California, and elsewhere in the Great Basin (Ferguson 1968; Salzer *et al.* 2014). Indeed, well-preserved subfossil baldcypress logs are present at most cypress swamps and have been essential for development of millennium-long chronologies in the southeastern United States (Stahle *et al.* 2012). Three *Austrocedrus chilensis* chronologies in Chile have recently been extended into the 7th Century AD using hundreds of fragments of relict wood, among the longest and most climatically sensitive tree-ring chronologies yet developed in South America. Ancient relict wood is widely present across the Colorado Plateau, especially in certain dry but fire-protected microsites, and was exploited by ancient human inhabitants of the region. If not recognized, this ‘‘old wood’’ problem can bias the interpretation of tree-ring and radiocarbon dates from prehistoric archaeological sites (Towner and Dean 2010). But relict wood is most importantly a key resource for long chronology development and replication, as the subfossil wood found on the Mancos River igneous outcrop clearly illustrates.

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