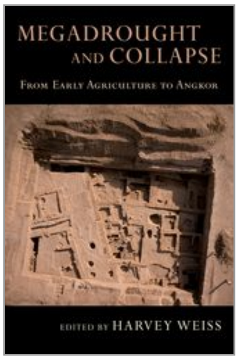

Megadrought and Collapse: From Early Agriculture to Angkor
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Thirteenth Century AD

Implications of Seasonal and Annual Moisture Reconstructions for Mesa Verde, Colorado

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Abstract and Keywords

The hypothesis that a prolonged drought across southwestern North America in the late thirteenth century contributed to the abandonment of the region by Ancestral Pueblo populations, ultimately including the depopulation of the Mesa Verde region, continues to be a focus of archaeological research in the Pueblo region. We address the hypothesis through the re-measurement of tree-ring specimens from living trees and archaeological wood at Mesa Verde, Colorado, to derive chronologies of earlywood, latewood, and total ring width. The three chronology types all date from AD 480 to 2008 and were used to separately reconstruct cool and early warm season effective moisture and total water-year precipitation for Chapin Mesa near many of the major prehistoric archaeological sites. The new reconstructions indicate three simultaneous cool and early growing season droughts during the twelfth and thirteenth centuries that may have contributed to the environmental and social factors behind Ancestral Pueblo migrations over this sector of the Colorado Plateau. These sustained inter-seasonal droughts included the “Great Drought” of the late-thirteenth century, which is estimated to have been one of the most severe regimes of cool and early summer drought in the last 1,500-years and coincided with the end of Puebloan occupations at Mesa Verde. The elevation of the 30 cm isohyet of water-year precipitation reconstructed for southwestern Colorado from the new ring-width data is mapped from AD 1276–1280 and identifies areas where dry-land cultivation of maize may not have been practical during the driest years of the Great Drought. There is no doubt about the exact dating of the tree-ring chronologies, but the low sample size of dated specimens from Mesa Verde during the late-thirteenth and fourteenth centuries contributes uncertainty to these environmental reconstructions at the time of abandonment.

Keywords: Ancestral Pueblo Collapse, dendrochronology, tree-ring, Mesa Verde, Colorado, Great Drought, 13th century ad North America

The hypothesis that a prolonged drought across southwestern North America in the late thirteenth century contributed to the abandonment of the region by Ancestral Pueblo populations, ultimately including the depopulation of the Mesa Verde region, continues to be a focus of archaeological research in the Pueblo region. We address the hypothesis through the remeasurement of tree-ring specimens from living trees and archaeological wood at Mesa Verde, Colorado, to derive chronologies of earlywood, latewood, and total ring width. The three chronology types all date from AD 480 to 2008 and were used to separately reconstruct cool and early warm season effective moisture and total water-year precipitation for Chapin Mesa near many of the major prehistoric archaeological sites. The new reconstructions indicate three simultaneous cool and early growing season droughts during the twelfth and thirteenth centuries that may have contributed to the environmental and social factors behind Ancestral Pueblo migrations over this sector of the Colorado Plateau. These sustained interseasonal droughts included the “Great Drought” of the late thirteenth century, which is estimated to have been one of the most severe regimes of cool and early summer drought in the last 1,500 years and coincided with the end of Puebloan occupations at Mesa Verde. The elevation of the 30 cm isohyet of water-year precipitation reconstructed for southwestern Colorado from the new ring-width data is mapped from AD 1276–1280 and identifies areas where dry-land cultivation of maize may not have been practical during the driest years of the Great Drought. There is no doubt about the exact dating of the tree-ring chronologies, but the low sample size of dated specimens from

Mesa Verde during the late thirteenth and fourteenth centuries contributes uncertainty to these environmental reconstructions at the time of abandonment.

(p.248)

Introduction

Modern Pueblo societies in New Mexico and Arizona have deep roots in the Four Corners region of the Colorado Plateau. Ancestral Pueblo society emerged by the early first millennium BC in southeast Utah, southwest Colorado, northwest New Mexico, and northeast Arizona. Population levels appear to have reached a maximum in southwestern Colorado during the early thirteenth century AD, and by the end of the century the Ancestral Pueblo had depopulated the region (Schwindt et al. 2016). Its subsistence base—dry-land cultivation of maize, beans, and squash, supplemented with wild foods and game—rendered Ancestral Pueblo society vulnerable to low crop yields during drought, and there is evidence linking decadal pluvials to village growth and decadal drought to village decline (Burns 1983, Barry & Benson 2010). Exact tree-ring dating of occupation sites and the tree-ring reconstruction of moisture conditions concurrent with the occupations provide, in part, the tight chronological control needed to draw close correspondences between long-ago climate and social dynamics.

There is little doubt that agricultural adaptations buffered Ancestral Pueblo society against drought, because these societies survived several intense decadal droughts during their long occupation of the Colorado Plateau. And yet the Four Corners region was fully abandoned by the Ancestral Pueblo by the close of the thirteenth century AD, when they relocated to north-central New Mexico and northern Arizona (Schwindt et al. 2016). Thus the role of the Great Drought (Douglass 1935) in Ancestral Pueblo abandonment of the Four Corners region remains a compelling focus of research, along with much that remains to be learned about past climate and these societies' social interactions (Kohler et al. 2010).

Mesa Verde, Colorado, in particular, has been an important area for dendrochronological research since the development of the tree-ring dating method in the early twentieth century (fig. 8.1). It is considered to be a type-site for tree-ring dating (Schulman 1946), including applications in dendroclimatology and dendroarchaeology. The first tree-ring dating of archaeological wood and charcoal from Mesa Verde was reported by A. E. Douglass during his development of Southwestern dendrochronology and the "Central Pueblo Chronology." Using tree-ring analysis, he dated prehistoric construction activity, identified the eventual cessation of construction, and advanced the hypothesis that prolonged drought in the late thirteenth century—the "Great Drought"—contributed to the abandonment of the region by Ancestral Pueblo populations (Douglass 1929, 1935, 1936). These ancient migrations, including the ultimate depopulation of the Mesa Verde region, continue to provide an important framework for archaeological research in the Pueblo region (see, for example, Kohler et al. 2010).

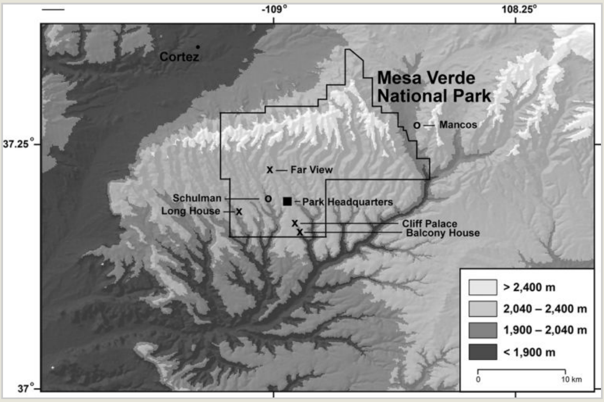


Figure 8.1 A digital representation of the terrain at Mesa Verde is mapped, along with the location of National Park boundary, major archaeological sites (x), selected tree-ring collection sites (o), and the headquarters weather station (black square).

Many subsequent studies have substantiated the occurrence of severe, sustained drought over the southwestern United States during the late thirteenth (p.249) century (for example, Euler et al. 1979, Dean & Funkhouser 1995, and Grissino-Mayer 1995). These are further supported by the gridded reconstructions of the Palmer drought severity index (PDSI) available in the North American Drought Atlas (Cook et al. 1999, 2004, 2007, 2010; Stahle & Dean 2011). However, the degree to which the drought may have promoted Ancestral Pueblo migrations remains unclear. Archaeological and dendrochronological evidence suggest that late thirteenth-century abandonment proceeded in an orderly fashion in the Kayenta region (Dean 2002), but appears to have been more chaotic in the Mesa Verde sector (Kohler et al. 2010). Agent-based models operating in a framework of reconstructed climate, soils, potential crop production, and wild food availability suggest that the carrying capacity of the environment was not completely exhausted during the late thirteenth century drought (see Dean et al. 2000, Kohler et al. 2005). According to these models, a reduced human population could have persisted in the region despite the extended dry conditions and, thus, drought alone cannot explain abandonment of the region.

Tree-ring based reconstructions of the maize niche in southwestern Colorado support conclusions derived from this agent-based model regarding the region’s carrying capacity during the worst of the thirteenth-century droughts (Bocinsky & Kohler 2014, Schwindt et al. 2016). However, the archaeological evidence indicates that the Mesa

Verde region was abandoned by the late thirteenth century, which leads Schwindt et al. (2016) to posit that earlier population increases in the region and expansion of the subsistence base into areas only marginally suitable for maize agriculture led to social stresses (p.250) during subsequent dry periods that contributed to instability and eventual societal collapse. The maize niche reconstructions reported by Bocinsky and Kohler (2014) are potentially testable in the archaeological record, but several factors in the study model render it inconclusive: the use of tree-ring chronology predictors located far from southwestern Colorado, the reconstruction of a discrete temperature record (that is, growing degree days) from moisture-sensitive tree-ring chronologies that integrate positive precipitation and negative temperature signals into a single ring-width response, and the lack of seasonal estimations of climate influence on the maize growing niche.

Because most tree-ring chronologies from the Colorado Plateau are sensitive to soil moisture variations determined by precipitation amounts during the winter-spring prior to the onset of the growing season (Fritts, Smith, & Stokes 1965), the degree to which the late thirteenth-century drought may have impacted the Ancestral Pueblo subsistence system, and especially its summer crop production, has been called into question (Gladwin 1947, Burns 1983, Adams & Petersen 1999, Kohler et al. 2005). Cool-season moisture conditions currently dominate the paleoclimate component of agent-based models (Dean et al. 2000) and maize-niche reconstructions (Bocinsky & Kohler 2014) for the region, all of which are based on annual ring-width chronologies. Discrete proxies of seasonal moisture conditions are needed to estimate prehistoric agricultural potential more realistically (Wright 2010). To that end, separate tree-ring chronologies based on the springwood and summerwood components of the annual ring have recently been developed for discrete reconstructions of cool- and warm-season moisture conditions (also referred to as earlywood and latewood; Meko & Baisan 2001, Stahle et al. 2009, Griffin et al. 2011, Stahle et al. 2015).

Mesa Verde Douglas fir (*Pseudotsuga menziesii*) trees have one of the strongest climate signals ever detected in tree-ring data. The physiology underlying their sensitive climate response is examined in a now-classic paper by Hal Fritts, David Smith, and Marvin Stokes (1965). The superb dating properties of the Mesa Verde Douglas fir have often been used to demonstrate the exact cross-synchronization of ring-width time series, which can be achieved with meticulous microscopic comparisons using the crossdating technique that

Douglass developed (1939, 1941). Schulman (1946) first documented the strong correlation between annual growth rings of Mesa Verde Douglas fir and winter-spring precipitation.

The annual growth rings of Douglas fir and other conifers reflect the climates of the previous autumn, winter, and spring—mostly prior to the summer season of cambial activity and radial growth at Mesa Verde and elsewhere on the Colorado Plateau (Fritts, Smith, & Stokes 1965). Consequently, these annual ring-width chronologies do not provide an unambiguous proxy of growing season climate conditions. Maize cultivation on the arid and relatively high-elevation Colorado Plateau can be constrained by low soil moisture, cool temperatures, and the length of the growing season (Hack 1942, Burns 1983, Petersen 1994). Winter-spring moisture is needed for germination and growth, but summer precipitation can also be important for maturation and yield (Adams & Petersen 1999, Benson et al. 2013). In fact, ongoing field experiments with the Pueblo Farming Project at the Crow Canyon Archaeological Center have highlighted the importance of winter-spring and July precipitation totals to selected varieties of maize (Mark Varien 2014, personal communication). If substantiated by further research, these findings would be favorable for improved tree-ring reconstructions of maize yields and maize niche space, because the earlywood and latewood components of the annual rings in such Southwestern conifers as Douglas fir and ponderosa pine (*Pinus ponderosae*) are especially sensitive to October-May and June-July precipitation totals, respectively (see, for example, Stahle et al. 2009, 2015; Griffin et al. 2012).

The annual rings of Douglas fir include anatomically distinctive earlywood and latewood cells. Because the boundary between these components of the species is usually abrupt, earlywood and latewood width within each ring can be measured precisely, and separate subannual ring-width chronologies can be computed to reconstruct past seasonal moisture levels (Schulman 1942, 1952, Meko & Baisan 2001, Stahle et al. 2009, Griffin et al. 2011). Here we report new chronologies of earlywood, latewood, and total ring width for Mesa Verde and use them to reconstruct cool and early warm season moisture levels and water-year total precipitation for the weather recording station on Chapin Mesa near the headquarters of Mesa Verde National Park. These new reconstructions are based on measurements of living trees and archaeological wood and charcoal from the national park, and they are restricted to the strongest seasonal climate signals detectable in these Douglas-fir proxies, namely September though June effective moisture for earlywood, just May and June effective moisture for latewood (that is, adjusted latewood, see below), and water-year total precipitation for annual ring width.

To a large degree we are repeating the analyses of Fritts, Smith, and Stokes (1965), who used annual ring-width data from archaeological and living Douglas-fir specimens to infer past climate for Mesa Verde, and Smith and Nichols (1967), who developed a 1529-year composite chronology of annual ring widths from living and archaeological Douglas fir. However, we add many new collections from living trees, partial ring chronologies of earlywood and latewood width, new reconstructions of winter-spring and early summer effective moisture, and a reconstruction of water-year precipitation totals. We compare these new reconstructions from Mesa Verde with other seasonal reconstructions based on earlywood and latewood width from the region and use them to identify episodes of simultaneous cool- and warm-season moisture deficits during the two centuries prior to the depopulation of southwestern Colorado by the Ancestral Pueblo. Two decadal regimes of cool and warm season drought are identified at Mesa Verde and in the nearby Mancos River region during the early and late thirteenth century. These highly unfavorable multi-season moisture conditions may have contributed to the environmental and social stresses that culminated in the final abandonment of the region.

(p.252) Data and Methods

Instrumental Climate Data

Data used in these analyses were obtained from two sources: (1) the weather station located on Chapin Mesa near the National Park headquarters where daily observations were started in 1922 (Figure 1; NOAA station ID 055531, Western Regional Climate Center, Desert Research Institute); and (2) the PRISM grid point located at 37.2ºN, 108.5ºW, and 2139-meter elevation, which is the point closest to the headquarters instrument site. The PRISM acronym refers to "Parameter-elevation Regressions on Independent Slopes Model" (Daly et al. 2002). The PRISM model essentially distributes the irregular and often sparsely located instrumental measurements of precipitation and temperature across a digital terrain surface, accounting for the effects of elevation, rain shadows, temperature inversions, and other factors on the local gridded climate. The database provides grid point estimates of monthly total precipitation, maximum temperature, minimum temperature, and other climate variables with a 4 kilometer resolution. The PRISM monthly precipitation data nearest to headquarters are nearly identical to the headquarters station record on a seasonalized basis. (For example, the two series are correlated for October-June total precipitation at $r = 0.99$, for May-June totals of the highest quality subperiod, AD 1948–2011, at $r = 0.98$, and for the AD 1924–1948 subperiod at $r = 0.94$ and 0.93.). The number of missing daily observations used to compute the monthly data for the headquarters record increases prior to 1949, and the PRISM model estimates these compromised monthly values from other stations in the Four Corners region. Both records are representative of the mesa top environment of Mesa Verde itself, which is close to many of the major archaeological sites.

Table 8.1 High-quality Measured and Dated Tree-ring Specimens

The individual tree-ring specimens used to develop the earlywood, latewood, and total ring-width chronologies for Mesa Verde, Colorado, are tabulated (identification number, inner and outer measured ring). Many additional dated tree-ring specimens from Mesa Verde are on archive at the University of Arizona Laboratory of Tree-Ring Research, of course, but here we selected all high-quality Douglas fir specimens that were relatively long, exhibited ring-width sensitivity, and covered important time periods over the past 1500 years. A few long series could not be located at the time of re-measurement. [Column 1 = sequence number; column 2 = series identification number; column 3 = first year dated and measured, column 4 = last year dated and measured] Schulman's old tree is identified as SOT01a-k (sequence numbers 60 to 70).

#	SPECIMEN	FIRST	LAST	#	SPECIMEN	FIRST	LAST
1	GP3165A	942	1118	32	MV I 029	960	1196
2	GP3 1 65B	942	1090	33	MV1O29B	961	1202
3	GP3 1 66	815	1060	34	MV1050B	930	1010
4	GP3166B	816	1022	35	MV1158A	888	1023
5	GP3166C	818	979	36	MV1158B	887	1010
6	GP3780	990	1145	37	MV1159A	858	1013
7	0P378013	990	1131	38	MV1159B	857	1030
8	GP3780C	990	1130	39	MVI I 59C	857	1002
9	GP3780D	990	1130	40	MV1159D	857	1010
10	GP3782	826	1120	41	MV1172	1060	1230
11	GP4477A	623	1000	42	MV 1172E	1090	1231
12	GP4477B	623	903	43	MVI 1 72C	1060	1222

#	SPECIMEN	FIRST	LAST	#	SPECIMEN	FIRST	LAST
13	GP4479	734	1141	44	MV1177A	846	1040
14	GP4480	850	1150	45	MV1177B	848	1040
15	GP4481	962	1142	46	MV1337	960	1106
16	GP4482	978	1130	47	MV1337B	939	1105
17	GP4483	989	1145	48	MV1337C	935	1090
18	GP5437	947	1010	49	MVI 390	695	801
19	GP5442	969	1023	50	MV2213A	554	690
20	GP6364	860	960	51	MV2213B	554	636
21	GP6502	880	1164	52	MV2258	690	803
22	GP6505	955	1130	53	MV2320	480	599
23	GP6524	1040	1127	54	MV2320B	480	545
24	MV169A	794	880	55	RFN1001	1283	1580
25	MV169B	850	950	56	MVD1	1405	1938
26	MV267	808	1010	57	MVD2	1462	1932
27	MV286	1024	1133	58	MVD8	1550	1937
28	MV286B	1024	1133	59	MVD1O	1680	1890
29	MV525	1181	1270	60	SOTOIA	1270	1820
30	MV525B	1181	1268	61	SOTO1B	1275	1850

#	SPECIMEN	FIRST	LAST	#	SPECIMEN	FIRST	LAST
31	MV525C	1210	1269	62	SOTO1C	1242	1950
63	SOTO1D	1220	1953	105	MVB08A	1619	1971
64	SOT01E	1311	1962	106	MVB08B	1536	1971
65	SOTOIF	1250	1962	107	MVB09A	1832	1971
66	SOTO1G	1227	1962	108	MVBO9B	1830	1971
67	SOTO1H	1237	1520	109	MVBIOA	1800	1971
68	SOTO I I	1260	1957	110	MVB1OB	1789	1971
69	SOTO1J	1252	1663	111	MVB11A	1648	1971
70	SOTOIK	1234	1961	112	MVBI I B	1600	1971
71	SOTO2A	1420	1750	113	MVB12A	1420	1971
72	SOTO2B	1480	1800	114	MVB12B	1390	1950
73	SOTO2D	1470	1861	115	BBD011	1638	1988
74	SOTO3A	1591	1962	116	BBD012	1697	1989
75	SOTO3B	1622	1962	117	BBD021	1762	1989
76	SOTO3C	1591	1954	118	13BD022	1812	1989
77	SOTO3D	1470	1962	119	BBD031	1600	1989
78	SOT03E	1470	1962	120	BBDO32	1622	1989
79	SOTO3F	1420	1960	121	BBD051	1607	1989

#	SPECIMEN	FIRST	LAST	#	SPECIMEN	FIRST	LAST
80	SOTO4A	1337	1960	122	BBD052	1629	1989
81	SOTO4B	1325	1962	123	BBD061	1600	1989
82	SOT04C	1375	1962	124	BBD071	1572	1989
83	SOTO4D	1321	1962	125	BBD072	1635	1989
84	SOTO4E	1326	1920	126	BBDO8 I	1600	1989
85	SOTO5A	1472	1930	127	BBD082	1704	1989
86	SOTO5B	1490	1880	128	BBD091	1763	1989
87	SOTO5C	1470	1950	129	BBD092	1810	1988
88	SOTO5D	1528	1930	130	BBD101	1390	1989
89	SOT06A	1469	1750	131	BBD102	1399	1930
90	SOT06B	1670	1800	132	BBDIl I	1785	1988
91	SOTO6C	1527	1950	133	BBD112	1798	1989
92	SOTO6D	1490	1960	134	SCM0 1 A	1792	2008
93	MVBO 1 *A*	1695	1972	135	SCMO 1 B	1797	1955
94	MVBOIB	1642	1950	136	SCMO2A	1726	2008
95	MVB03A	1631	1971	137	SCMO2B	1720	2008
96	MVB03B	1619	1971	138	SCM04A	1798	2008
97	MVB04A	1820	1971	139	SCM04B	1823	2008

#	SPECIMEN	FIRST	LAST	#	SPECIMEN	FIRST	LAST
98	MVB04B	1690	1971	140	SCM05A	1784	2008
99	MVB05A	1825	1971	141	SCM05B	1775	1948
100	MVB05B	1746	1971	142	SCM06A	1537	2008
101	MVB06A	1630	1920	143	SCM06B	1520	2008
102	M VE106B	1700	1972	144	SHMO2A	1434	2008
103	MVBO7A	1644	1972	145	SHMIOB	1585	2008
104	MVB07B	1597	1971	146	SHMO3A	1693	2008
147	SHMO3B	1701	2008	157	SHM13A	1479	2008
148	SHMO6A	1812	2008	158	SHM15A	1587	2008
149	SHMO6B	1623	1834	159	SHM15B	1515	2008
150	SHMO7A	1531	2008	160	SHM16A	1890	2008
151	SHMO7C	1740	2008	161	SHM16B	1890	2008
152	SHMO8A	1630	2008	162	SHM17A	1818	2008
153	SHMO9A	1854	2008	163	SHM17B	1818	2008
154	SHMO9B	1854	2008	164	SHM20A	1544	2008
155	SHM10A	1609	2008	165	SHM2 IA	1839	2008
156	SHMIOB	1609	2008	166	SHM 21B	1587	2008

Tree-Ring Data

Over 160 tree-ring specimens obtained from living trees and archaeological wood and charcoal were re-measured to develop separate earlywood (EW), latewood (LW), and total ring (TR) width chronologies. The tree-ring specimens were all Douglas fir from Mesa Verde and were originally dated at the Laboratory of Tree-Ring Research in Tucson (Table 8.1). The collection includes archaeological samples dated by A. E. Douglass and cores from living trees dated by E. Schulman. The specimens were remeasured for EW, LW, and TR width to a precision of 0.001 millimeters using the procedures outlined in Schulman (1952) and Stahle et al. (2009). This level of measurement precision is necessary to quantify the often-minute latewood variance on microscopic rings.

The measurements of EW, LW, and TR width were screened for dating and measurement accuracy with correlation analyses among all dated specimens using the computer program COFECHA (Holmes 1983. The program ARSTAN (Cook 1985, Cook & Krusic 2005) was used to compute the detrended robust (p.253) (p.254) (p.255) mean index standard chronologies of EW, LW, and TR width. No dating or measurement errors were discovered in this exceptionally sensitive tree-ring collection, although the LW width series are not as strongly cross-correlated as the EW or TR width series. For the EW, LW, and TR series, the mean correlation (RBAR) statistics from ARSTAN are 0.71, 0.42, and 0.70, respectively. The coherence among these Douglas-fir series is exceptionally strong for EW and TR width. The mean correlation among the LW series is not as strong as might be typical of arid site TR width collections, but that is a very high standard indeed and their agreement is still highly significant and useful for paleoclimatic reconstruction.

For this analysis, we detrended each measured time series twice, first fitting a negative exponential curve to remove the non-climatic growth trend due to the increasing age and size of the trees, and then a cubic smoothing spline with a 50 percent frequency response equal to 67 percent of the series length to minimize poor curve fitting effects especially near the beginning and end of the time series. This detrending prescription was used for all three data types (EW, LW, TR width) and preserves more low frequency variance in the longer series. The numerical ring-width measurements and derived chronologies, along with the seasonal climate reconstructions, are all provided at http://www.uark.edu/dendro/MVdata.xisx.

To remove the strong correlation between the derived EW and LW standard chronologies (r = 0.81; AD 480–2008), we regressed the LW width chronology on the EW width chronology using robust regression to discount outliers (using standard chronologies in both cases). The residuals from the regression of LW on EW were then used to represent the early warm season climate independent of the physiological persistence of growth within the annual ring [that is, the adjusted LW (LW_{adj}); Meko & Baisan 2001; Stahle et al. 2009]. We used correlation analysis to model the EW and LW_{adj} response to monthly moisture variables and to identify the optimal seasons for climate reconstruction.

The absolute tree-ring dating of Mesa Verde ruins was not achieved using long-lived trees local to the mesa. Rather the ruins were initially dated with reference to the Central Pueblo Chronology developed from old living trees, colonial era building timbers, and prehistoric wood and charcoal which were concentrated in the vicinity of northeastern Arizona and northwestern New Mexico (Douglass 1935). The famous temporal gap between the chronology based on the living trees and the floating chronology compiled from the archaeological specimens was finally closed with certainty with wood recovered near Showlow, Arizona (Douglass 1935, Haury 1962). Old living trees that actually date back over 700 years to the era of heavy prehistoric occupation are very rare at Mesa Verde. Only one Douglas-fir tree has been found that actually dates to the thirteenth century and crossdates with the archaeological wood on the mesa: an 800-year old individual discovered by Schulman (1947) several years after the initial dating of the ruins. Thus, the period when severe drought appears to have persisted over the Colorado Plateau and the mesa was being depopulated by Ancestral Pueblo is represented locally by tree-ring data available from only one tree. (Descriptive data on Schulman’s old tree are listed in Table 8.1 as SOT01a-k).

There is no doubt regarding the absolute dating of Schulman’s old tree or of the archaeological sites at Mesa Verde, of course, which all correlate with the regional master chronology first developed by Douglass and subsequently by others. But the magnitude and persistence of late thirteenth century drought at Mesa Verde itself is less certain because the sample size of the tree-ring data is so low. We have not been able to add any additional tree-ring sequences to this crucial time period, but we do provide statistical evidence that lends some confidence to the portion of the Mesa Verde Douglas-fir chronology that is represented only by Schulman’s old tree (below). We also include analyses of cool- and warm-season precipitation reconstructions developed from recent remeasurements of EW and

LW_{adj} at El Malpais, New Mexico (Grissino-Mayer 1995, Stahle at al. 2009), for a broader perspective on seasonal drought during the thirteenth century at Mesa Verde.

Reconstruction Methods

The seasonal climate response of the EW, LW_{adj}, and TR width chronologies was investigated using correlation analysis between the chronologies and monthly precipitation, maximum temperature, and an effective moisture index during the year prior to and concurrent with tree growth (year *t-1* and *t*, respectively). The effective moisture index was computed for the PRISM grid point as the difference between total monthly precipitation and potential evapotranspiration, or P-PE. Potential evapotranspiration was computed from the monthly mean temperature of minimum and maximum temperatures available at the PRISM grid point using the Thornthwaite method (1948, Burnette & Stahle 2013). The monthly P-PE estimates were transformed into anomalies by subtracting the mean P-PE for the 1895–2011 period of record. Positive P-PE values represent wet and cool conditions, and negative values are dry and warm. Because one goal of this research has been to reconstruct restricted seasonal moisture variables from EW and LW_{adj} chronologies, this P-PE index does not include any prescribed month-to-month persistence to model soil moisture storage.

To develop the reconstructions, the tree-ring chronologies and three lead and lagged versions were entered into forward stepwise regression as potential predictors of October-June P-PE for EW, May-June P-PE for LW_{adj}, and October-September precipitation for TR width. Autoregression in the predictor and predictand time series during the calibration period was identified using the corrected Aikaike Information Criteria (AICc; Cook et al. 1999), and any persistence in the time series was removed prior to calibration. The derived reconstructions were tested against independent climate data withheld from the calibration, and the degree of fit between observed and estimated data was evaluated graphically and with the Pearson correlation (r), reduction of error (RE), and coefficient of efficiency (CE) statistics (Cook et al. 1999). To estimate the amount of variance in effective moisture that might be represented during the poorly replicated portion of the chronology in the late thirteenth and early fourteenth century, we also calibrated EW and LW_{adj} chronologies based only on the eleven cores from Schulman’s old tree.

Results

Seasonal Moisture Response

The correlation coefficients computed between the tree-ring chronologies and monthly precipitation, maximum temperature, and P-PE are plotted in figure 8.2. EW width is significantly and positively correlated with precipitation during the winter-spring season preceding tree growth from September through May (fig. 8.2a) and is negatively correlated with monthly mean maximum temperature from September through July (fig. 8.2b). This is the same basic precipitation and temperature response previously documented for Douglas-fir EW width on the Colorado Plateau (Cleaveland 1983, 1986; Stahle et al. 2009) and for TR width at Mesa Verde (Fritts et al. 1965) and can be represented by a single variable that measures effective moisture, the P-PE index. Because the EW chronology is positively correlated with monthly P-PE continuously from September through June (fig. 8.2c), the effective moisture signal averages the late spring-early summer precipitation and temperature responses (ending in May and July, respectively).

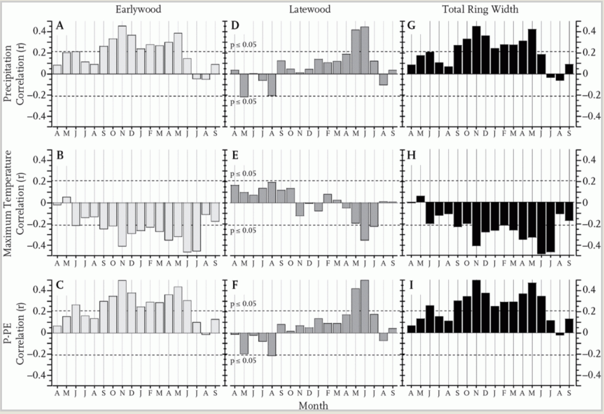


Figure 8.2 Correlations of the earlywood width chronology with monthly precipitation (*a*), maximum temperature (*b*), and P-PE (*c*) for the year prior and concurrent with tree growth (prior April through current September), using the PRISM grid point closest to the headquarters rain gage at Mesa Verde, National Park (1923–2008). Adjusted LW width is also correlated with monthly precipitation (*d*), maximum temperature (*e*), and P-PE (*f*) for the same PRISM grid point. Total ring width (TRW) is correlated with these same variables for the water year (October-September; *g, h,* and *i*).

The cool season moisture response of EW width at Mesa Verde is nearly identical to the response of total ring width (fig. 8.2), simply because EW represents the major fraction of annual ring width (that is, mean EW width = 0.348 mm, mean LW width = 0.111 mm, mean TR width = 0.459 mm, or 76 and 24 percent on average for EW and LW, respectively). Chronologies of EW and TR width can both be used to develop verifiable reconstructions (p.258) of water-year precipitation or P-PE totals at Mesa Verde. But the strongest climate signal for EW is confined to moisture variation during the winter-spring season (fig. 8.2c), largely prior to the onset of radial growth that may begin in March, but 90 percent of which occurs only in May for Mesa Verde Douglas-fir (Fritts et al. 1965). Thus the conclusion that “climate previous to the growing season has a greater effect on ring width than climate during the growing season” (Fritts, Smith, & Stokes 1965) applies to both EW and TR width. The LW_{adj} chronology, on the other hand, is significantly correlated with climate early in the growing season concurrent with the formation of LW cells (fig. 8.2def).

The response of the raw LW chronology, prior to the adjustment of LW width for dependency on EW width, is also dominated by climate during the winter-spring, well before the formation of LW cells (not shown). The regression of the LW chronology on the EW chronology is necessary to obtain a direct estimate of early growing season climate conditions not heavily influenced by preceding climate and tree growth (EW) variables. The correlation between the LW_{adj} chronology and monthly precipitation, maximum temperature, and P-PE values indicates that the adjustment has worked reasonably well. Adjusted LW is significantly and positively correlated with precipitation and P-PE only in the months of May and June concurrent with tree growth, and it is negatively correlated with maximum temperature only in June and July (fig. 8.2def).

The monthly moisture response of EW does overlap with the response of LW_{adj} in May and June, depending on which climate variable is being considered (fig. 8.2). However, the two series are not strongly correlated (r = 0.13, AD 480–2008); the EW chronology is dominated by climate prior to the onset of growth, and the LW_{adj} is dominated by climate concurrent with growth in the May-June period. The two partial ring chronologies therefore provide reasonably discrete estimates of cool and early warm season moisture for Mesa Verde.

Calibration and Verification of the Seasonal and Water-Year Moisture Reconstructions

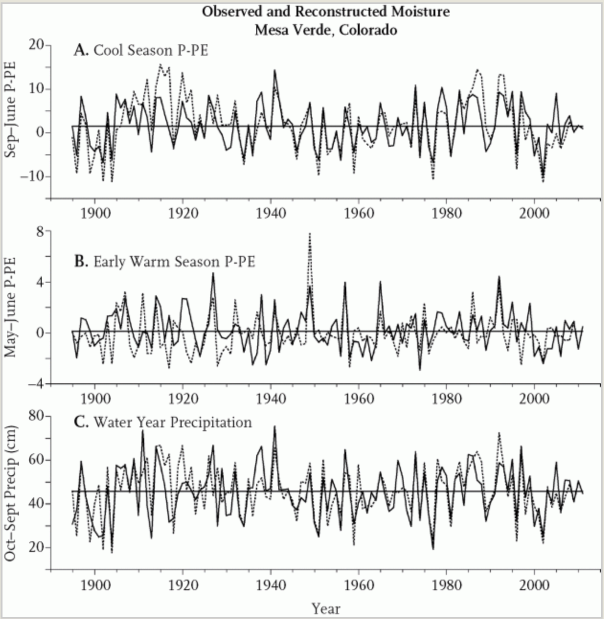


Figure 8.3 (*a*) The observed (solid) and reconstructed (dashed) cool-season moisture balance values (P-PE) are plotted for the Sept-June season at the PRISM grid location closest to the headquarters weather station at Mesa Verde National Park (based on EW width). The calibration period was AD 1923–1966 and the verification period was 1967–2008. The EW chronology is also correlated with the PRISM P-PE at the Mesa Verde grid location from 1895–1922, though not as well as after 1922, when local weather observations began at the headquarters station. (*b*) Same as (*a*) for the early warm season (May-June, based on adjusted LW width). The LW_{adj} is not correlated with the PRISM-based P-PE before 1923, the year observations began at the headquarters weather station at Mesa Verde. *(c)* Same as (*a*) for water-year precipitation (October-September) reconstructed from TRW.

The EW chronology for Mesa Verde Douglas-fir and six lead and lagged versions (the robust mean standard EW width chronology in years *t-3, t-2, t-1, t, t+1, t+2, t+3*) were submitted to forward stepwise regression to estimate Sept-June P-PE for the PRISM grid point nearest to headquarters at Mesa Verde National Park. The potential predictors were screened for correlation with Sept-June P-PE ($p < 0.10$) and only the EW chronology in year *t* was selected—that is, the chronology representing EW growth beginning in May near the end of the Sept-June P-PE season). The resulting bivariate regression model used to estimate Sept-June effective moisture was:

$$\hat{Y}_t = -9.059 + 10.937X_t$$

(1)

where $\hat{Y}_t$ is reconstructed P-PE in year *t* for the Sept-June season and X_t is the EW width chronology also in year *t*. Prior to the regression, autoregressive modeling detected no persistence in either variable based on the AICc during (p.259) (p.260) the short calibration interval, 1923–1966 (Cook et al. 1999). The EW chronology explains nearly two-thirds of the variance in the Sept-June effective moisture index during the 1923–66 calibration period (coefficient of determination, adjusted for the loss of one degree of freedom, $R^2_{adj} = 0.648$) and the residuals from regression do not exhibit serial correlation or other serious deficiencies (see Durbin-Watson statistic, Table 8.2). The observed and reconstructed P-PE (p.261) indices for the September-June season are plotted in figure 8.3a from 1923–2008, and observed and reconstructed values are significantly correlated during the 1967–2008 validation period at $r = 0.79$ ($p < 0.0001$, Table 8.2). The RE and CE statistics indicate that the reconstruction is reproducing approximately 61 percent of the instrumental variance when compared with independent P-PE indices from 1967–2008.

Table 8.2 Calibration and Verification Statistics

Calibration and verification statistics computed for the reconstruction of cool (September-June) and early-summer (May-June) moisture balance (P-PE), and water year precipitation totals (October-September) at Mesa Verde, Colorado. The calibration interval is listed first (e.g., 1923–1966), followed by the verification interval (e.g., 1967–2008) 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. The Pearson correlation coefficient, comparing reconstructed with instrumental P-PE data during the statistically independent verification periods, is 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, although the early-summer reconstruction based on LW_{adj} is considerably weaker than the EW reconstruction of the September-June moisture balance or the TRW estimate of water year precipitation.

TIME PERIOD	COEFFICIENTS		CALIBRATION			VERIFICATION		
Sept–June	**b_0**	**b_1**	**R^2_{adj}**	**SE**	**DW**	**r**	**RE**	**CE**
1923–1966	−9.06	10.94	0.64	2.79	1.93			
1967–2008						0.79	0.63	0.62
May–June	**b_o**	**b_1**	**R^2_{adj}**	**SE**	**DW**	**r**	**RE**	**CE**
1923–1966	−4.83	2.48	0.37	1.40	2.12			
1967–2008						0.48	0.21	0.20
Oct–Sept	**b_o**	**b_1**	**R^2_{adj}**	**SE**	**DW**	**r**	**RE**	**CE**
1949–2008	0.00	9.40	0.65	2.69	2.03			
1896–1948						0.57	0.26	0.26

The Douglas-fir adjusted LW chronology was submitted to a forward stepwise regression to estimate the PRISM May-June effective moisture (with leads and lags) and once again only the $\mathrm{LW_{adj}}$ chronology in year *t* passed the screening. Thus, a bivariate regression model was also used to estimate May-June P-PE:

$$\hat{Y}_t = -4.831 + 2.479 X_t$$

(2)

(p.262) where $\hat{Y}_t$ is reconstructed P-PE in year *t* for the May-June season and X_t is the adjusted LW width chronology also in year *t*. No autoregressive structure was detected in either regression variable, but in this case the $\mathrm{LW_{adj}}$ only explains 37 percent of the variance during the calibration period (R^2_{adj} = 0.372, 1923–1966; Table 8.2). The relationship between $\mathrm{LW_{adj}}$ and May-June P-PE is also subject to some temporal instability (figure 8.3b), and this is evident in the validation statistics where the observed and reconstructed values are correlated at r = 0.483 from 1967–2008, and the RE and CE indicate only modest validation skill (0.21 and 0.20, respectively; Table 8.2). The $\mathrm{LW_{adj}}$ chronology calibrates and verifies somewhat better against May-June precipitation totals (for example, R^2_{adj} = 0.43 and RE = 0.28 for 1922–1966), but there is still considerable temporal variability in the relationship, and the model estimates some negative May-June precipitation totals. The P-PE reconstruction from $\mathrm{LW_{adj}}$ was therefore deemed better in overall performance.

May and June are two of the driest months on average at Mesa Verde and precipitation during this season may be spatially discontinuous. For this reason it can be more difficult to calibrate $\mathrm{LW_{adj}}$ chronologies against station or regional average precipitation data (for example, Stahle et al. 2009). But some of the noise in the relationship between May-June moisture levels and the $\mathrm{LW_{adj}}$ chronology at Mesa Verde must arise from the strong correlation between EW and raw unadjusted LW width (r = 0.81, AD 480–2008). When this much shared variance is removed in regression, in this case presumably due to the common winter-spring climate signal and physiological persistence in growth, some of the residual variance must be random noise unrelated to climate. That some 20 to 37 percent of the variance in May-June moisture levels can be recovered from the adjusted LW chronology at Mesa Verde is interesting in light of the very strong common signal between EW and raw LW width.

The Douglas-fir TRW chronology was also submitted to a forward stepwise regression to estimate water-year precipitation totals (October-September, with leads and lags) based on the calibration period of 1949–2008. With only the TRW chronology in year *t* passing the screening, the following regression model was used to estimate water-year precipitation:

$$\hat{Y}_t = -0.004 + 9.40X_t$$

(3)

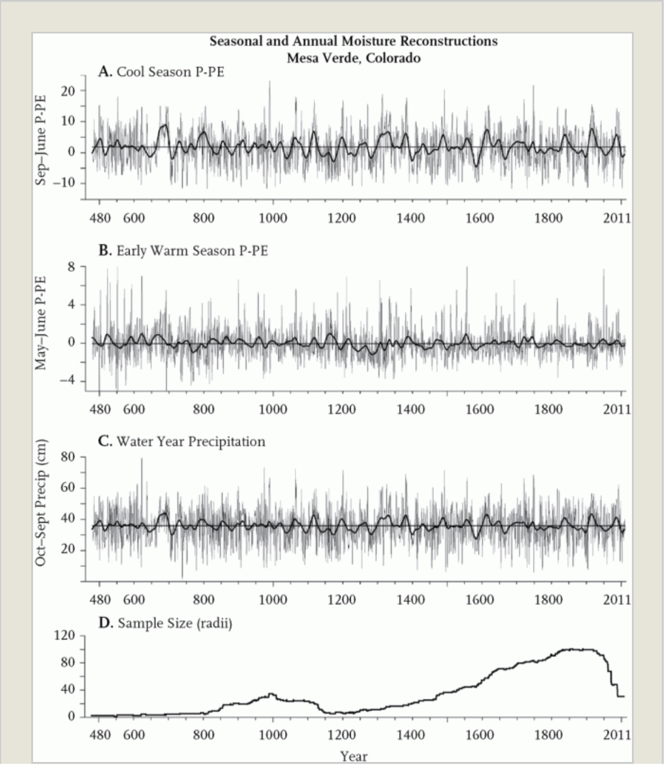
where $\hat{Y}_t$ is reconstructed water-year precipitation in year *t* and X_t is the TR width chronology also in year *t*. No autoregressive structure was detected in either regression variable during the calibration period. The TRW chronology explains 65 percent of the variance in water-year precipitation during the calibration period, but the verification statistics indicate that observed and reconstructed precipitation are not as tightly coupled during the period 1896–1948 (for example, r = 0.57; Table 8.2).

These calibration and verification results are based on well-replicated twentieth century tree-ring chronologies. However, several cores from only one tree represent the chronologies for the period in the late thirteenth (p.263) century when Ancestral Pueblo left Mesa Verde (that is, 1271–1282). It is therefore reasonable to question the strength of the seasonal and water-year response of this single old Douglas-fir tree. Our analyses indicate that the climate signals in Schulman’s single old tree are quite good. Seasonal precipitation totals instead of P-PE and different calibration and verification periods had to be used to derive the best models during the 1895–1962 period in common to both the Schulman chronologies and the PRISM climate data. Nevertheless, the EW chronology from Schulman’s old tree explains 56 percent of the October-May precipitation, the $\mathrm{LW_{adj}}$ chronology explains 25 percent of the May–June precipitation, and the TRW chronology explains 58 percent of the October-September precipitation (all calibrated from 1940 to 1962). Verification of the reconstructions during the 1895–1940 period is only marginal, but it is still extraordinary that EW, $\mathrm{LW_{adj}}$, and TR width data from only one tree can successfully estimate cool, water-year, and—to a lesser extent—even early warm-season moisture levels. In fact, the two reconstructions of cool season moisture are correlated at r = 0.93 from 1220 to 1962 (that is, September-June P-PE versus October-May total precipitation during the period covered by our EW data derived from Schulman’s old tree) and the two early warm-season reconstructions, at r = 0.77 (that is, May-June P-PE versus May-June total precipitation, 1220–1962). Even during the 162-year period from 1801–1962 when Schulman’s old tree was really old (over 600 years), the two reconstructions are still well correlated at r = 0.93 and 0.66 for the cool and early warm seasons, respectively.

Analysis and Discussion

Seasonal Moisture Reconstructions for Mesa Verde

The EW reconstruction of September-June effective moisture is plotted along with a smoothed version emphasizing decadal regimes over the past 1529 years (480–2008, fig. 8.4a). The driest single year in the entire reconstruction was estimated for 2002, which was also the most negative P-PE value measured for the September-June period in the instrumental PRISM data from 1923–2011 (the period of operation for the nearby headquarters weather station). The worst multiyear drought episode in the September-June reconstruction is estimated to have occurred in the late sixteenth century (fig. 8.4a), when severe sustained drought conditions were present over a large fraction of western North America (see, for example, Meko et al. 1995, Stahle et al. 2000, Herweijer, Seager, & Cook 2006). The medieval era was marked by several prolonged cool season droughts at Mesa Verde, especially during the twelfth and thirteenth centuries. This 200-year period of dryness was occasionally interrupted by above average conditions, of course, but prolonged drought nevertheless prevailed and was finally terminated by a major multidecadal pluvial in the early fourteenth century (fig. 8.4a). (p.264) (p.265)



The annual and decadal values of the May-June effective moisture reconstruction are plotted in figure 8.4b, and the number of dated radii each year is plotted for both EW and LW in Figure 4c. The variance structure of instrumental and reconstructed May-June P-PE is substantially more skewed than Sept-June P-PE (figs. 8.3–8.4), and early summer P-PE is dominated by the episodic occurrence of very high values. The decadal variability of reconstructed May-June P-PE is also much lower than the decadal variance in the Sept-June reconstruction, in part because so much common variance between EW and LW was removed in order to adjust the LW. The most severe and prolonged May-June drought is reconstructed during the late thirteenth century, when sample size is restricted to Schulman’s Old Tree, even though several individual years are estimated to have been well above average. Prolonged May-June drought is also estimated during the early thirteenth century, and during the eighth and fifteenth centuries (fig. 8.4b).

Figure 8.4 *(a)* The cool season moisture balance reconstruction for Mesa Verde, Colorado, based on EW width is plotted from AD 480 to 2008 (September-June total P-PE in gray, 30-year smoothing in black). Note the generally below average cool season moisture conditions estimated for the twelfth, late thirteenth, late fourteenth, and late sixteenth centuries. *(b)* Same as *(a)* for the early warm season (May-June total P-PE in gray, 30-year smoothing in black). Prolonged below average early warm-season moisture conditions are reconstructed during the late-thirteenth century, but from 1271 to 1282 the cool and warm season reconstructions are both based on just nine radii from Schulman’s single old tree *(d)*. Sample size is also low before 700 and may be partly responsible for the heightened variance during the first two centuries of this reconstruction. *(c)* Same as *(a)* for water-year precipitation totals based on TRW (October-September).

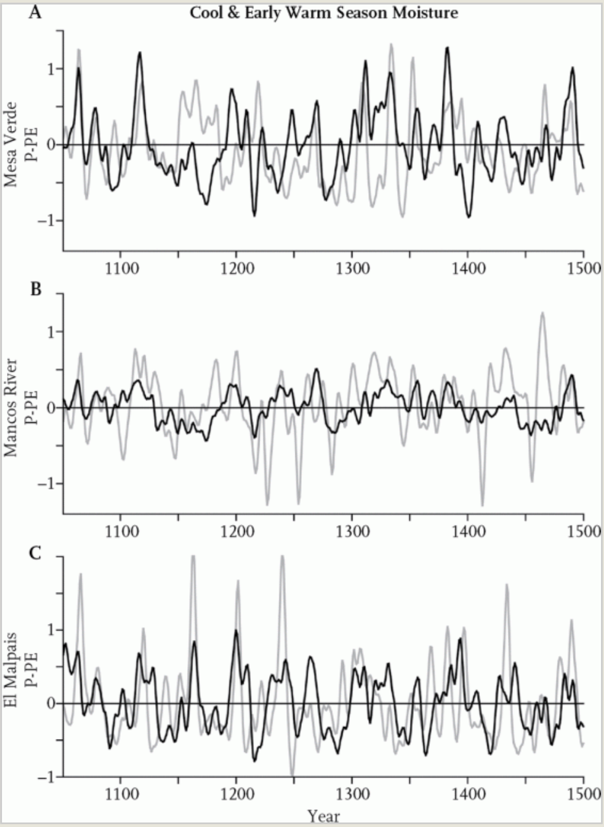


Figure 8.5 *(a)* Normalized and smoothed reconstructions of cool (black) and early warm season (gray) moisture conditions are plotted from AD 1051 to 1500 for Mesa Verde *(a),* Mancos River *(b),* and El Malpais *(c)* [i.e., Sept-June and May-June for Mesa Verde, Sept-May and June-July for Mancos, and Nov-May and July for El Malpais; spline smoothing to highlight 10-year variability (Cook and Peters 1981)].

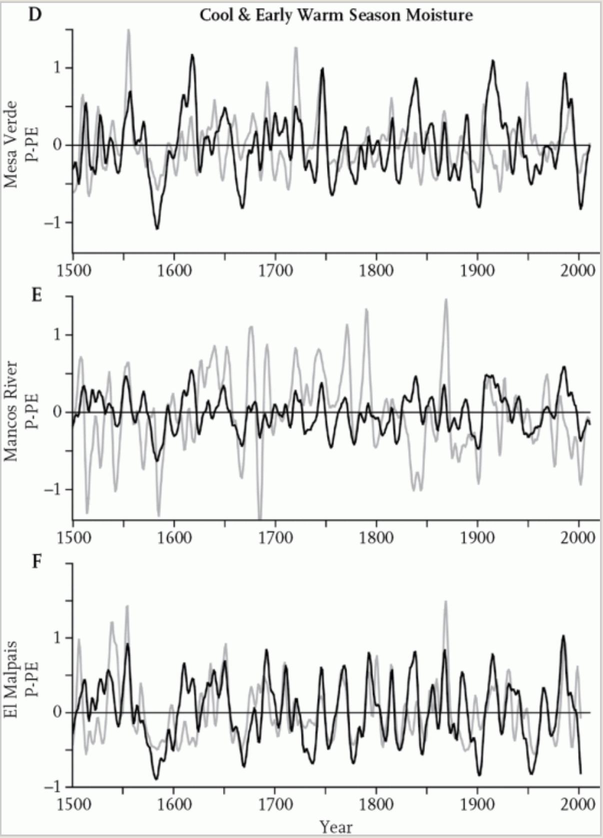


Figure 8.6 Same as fig. 8.5 for the period 1501-present for Mesa Verde *(d),* Mancos River *(e),* and El Malpais *(f)*.

Simultaneous Cool and Early Growing Season Moisture Estimates

The cool and early warm season reconstructions were normalized, zero-centered, and smoothed to compare ca. 10-year regimes of seasonal moisture at Mesa Verde, Mancos River, Colorado (from Stahle et al. 2015), and El Malpais National Monument, New Mexico (from Stahle et al. 2009). The z-scores were computed for each reconstructed value by subtracting the median and then dividing by the inter-quartile range. These smoothed cool- and warm-season reconstructions are plotted together from 1051 to the present in figures 8.5 and 8.6, and just from 1101 to 1350 during the heavy Ancestral Pueblo occupations of southwestern Colorado in figure 8.7. The reconstructions indicate that the droughts during the early- and late-thirteenth century were among the most severe and sustained dual-season droughts of the last millennium (that is, during the 1051-2002 period in common to the three site recons; figs. 8.5 and 8.6). A multi-season megadrought during the sixteenth century likely exceeded all droughts of the past millennium, but the prolonged deficits in cool-season moisture in the late thirteenth century at all three locations were unusual in the context of the past millennium, and they were likely made worse in terms of environmental and socioeconomic impacts by the co-occurrence of shorter drought periods during the growing season.

Dual-season drought also occurred earlier in the thirteenth century over southwestern Colorado and west-central New Mexico (fig. 8.7). Dual-season drought began in the 1210s at Mancos River and El Malpais, developed in the 1220s, and persisted into the 1240s at Mesa Verde. (The sample size is low at Mesa Verde during this period.) Note especially the large magnitude warm-season droughts reconstructed at Mancos River in the 1210s, 1220s, and 1250s (fig. 8.7). These warm season extremes at Mancos River were matched by decadal excursions at El Malpais, but with somewhat different timing and intensity. Prolonged dual-season drought is reconstructed from 1170 to 1190 at (p.266) El Malpais during a period of contrasting seasonal moisture regimes in southwestern Colorado (fig. 8.7). Finally, as figure 8.7 shows, the early fourteenth century was general wetter in both seasons, with the exception of the 1320s at Mesa Verde, which is represented only by Schulman’s old tree.

The smoothed moisture reconstructions from Mesa Verde, Mancos River, and El Malpais are more consistent during the cool season (figs. 8.5–8.7). The early warm-season estimates are less coherent due in part to low sample (p.267) size at Mesa Verde, slight differences among the sites in the monthly climate response of adjusted LW width, and the fact that a large proportion of shared variance was removed from the LW_{adj}

chronologies when they were regressed against EW width. Additional warm-season moisture proxies will be needed from the region to improve the estimates of growing season moisture. But the reconstructions all indicate that the thirteenth century was marked by at least two episodes of simultaneous drought during the cool- and early-warm season over southwestern Colorado and northwestern New Mexico.

The new reconstructions generally do not indicate that the late thirteenth century experienced drought in the cool season, but wetness in the summer, (p.268) a hypothesized climate scenario that may have ameliorated to some extent the impacts of prolonged cool season drought on native subsistence systems (Gladwin 1947). Fritts, Smith, & Stokes (1965) also did not find support for a strongly out-of-phase pattern of cool and warm season moisture during the Great Drought of the late thirteenth century. But their inferences and ours do not entirely rule out the wet summer hypothesis for the late thirteenth century, because full summer climate conditions (JJAS) are not represented in our reconstructions based on adjusted LW width, and the summer signal detected by Fritts, Smith, and Stokes cannot be isolated from the suite of previous summer, autumn, winter, and spring climate factors that explain annual (p.269) ring width in their model. Figure 8.7 does indicate that most of the thirteenth century was relatively dry during May-June at Mesa Verde, June-July at Mancos River, and July at El Malpais. Thus, to the extent that growing season moisture was important to the subsistence base of the Ancestral Pueblo at Mesa Verde, reconstructed warm-season conditions were unlikely to have mitigated winter-spring drought effects during the late thirteenth century. In fact, some of the most extremely dry warm-season conditions are estimated during the thirteenth century in the Mesa Verde-Mancos River area, including one of the worst episodes of simultaneous cool- and warm-season drought reconstructed during the 250-year period from 1101 to 1350 or during the entire period covered by these dual season reconstructions (see also Stahle et al. 2015). These unfavorable seasonal moisture conditions likely contributed to the growing instability in Ancestral Pueblo societies in southwestern Colorado. The decline in regional populations had apparently begun well before the late thirteenth-century dual season drought, perhaps in partial response to simultaneous cool- and warm-season droughts over the region in the early thirteenth century (fig. 8.7).

Finally, the reconstructions in figures 8.4a, b, and c do not indicate that the thirteenth-century drought was exceeded by at least ten other droughts over the past 1500 years, as was posited by Fritts, Smith, and

Stokes, based on five-year running means of the total ring-width index of selected archaeological and modern Douglas fir. This is particularly true when we consider simultaneous cool- and warm-season drought at Mesa Verde, Mancos River, and El Malpais (figs. 8.5–6). By these measures, the thirteenth century appears to have been one of the most persistently dry warm-season regimes, with some of the most intense episodes of simultaneous cool and early summer drought of the last 1000 years. Dual season drought conditions over the Mesa Verde region appear to have been equaled or exceeded by simultaneous droughts only in the mid-seventeenth, late nineteenth, and early twenty-first centuries, and especially during the late sixteenth-century megadrought.

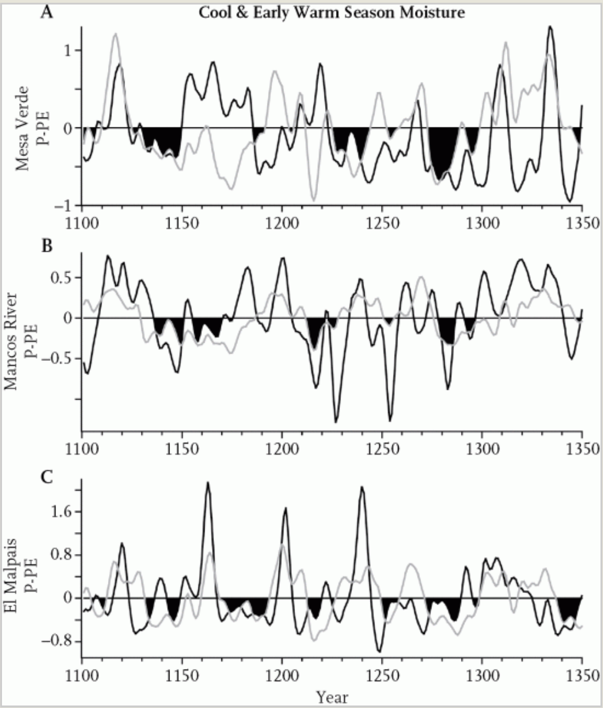


Figure 8.7 Similar to Figure 5, but here the normalized and 10-year smoothed reconstructions of cool and early warm-season moisture conditions are plotted only from AD 1101 to 1350 for Mesa Verde *(a),* Mancos River *(b),* and El Malpais *(c).* Note that the cool season is plotted here in gray, warm season in black, and the episodes of simultaneous cool- and warm-season drought are shaded black (i.e., normalized P-PE or

PPT for both the cool and warm season are ≤ 0.00).

Conclusions

The new seasonal moisture reconstructions indicate that the “Great Drought” of the late thirteenth century included severe and sustained moisture deficits during both the cool and early warm season. They also indicate that the Great Drought was preceded by dual-season drought conditions in the early- to mid-thirteenth century and that dry conditions in the early warm season prevailed over a large portion of the Four Corners during the entire century. The archaeological record indicates that immigration and depopulation were multidecadal processes at Mesa Verde and culminated in complete abandonment by the close of the thirteenth century (Varien 2010, Schwindt et al. 2016). The co-occurrence of cool and early warm-season drought during the thirteenth **(p.270)** century may have contributed to the environmental and social stresses that stimulated these migrations among Ancestral Pueblo.

The new cool and early warm-season moisture reconstructions could yield improved estimates of crop yields and the maize niche over the Mesa Verde region (Kohler 2010, Bocinsky & Kohler 2014, Schwindt et al. 2016). Douglas-fir LW chronologies at Mesa Verde, Mancos River, and El Malpais are not correlated with precipitation or temperature during August or September (fig. 8.2), but selected LW chronologies of ponderosa pine (*Pinus ponderosa*) do respond to late summer precipitation elsewhere in the Southwest (Griffin 2013). Development of ponderosa pine LW chronologies spanning the period of Puebloan occupations is a possibility (for example, Guiterman et al. 2016) and could improve reconstructions of regional summer moisture considerably.

Finally, the chronological gap in the late thirteenth and early fourteenth century that was so problematic during the development of Southwestern dendrochronology (Douglass 1935, Haury 1962) remains a serious replication issue impacting the paleoclimatic inferences on occupation and migration that can be derived from these outstanding tree-ring proxies. The long tree-ring chronologies developed from living trees and subfossil wood at El Malpais and Mancos River are proof that replication for this important episode in environmental and Ancestral Pueblo history can be improved. Given the importance of environmental variability to archaeological analyses of Ancestral Pueblo migrations and the very sparse tree-ring record presently available during key time periods at Mesa Verde, we still need to develop exactly dated, well-replicated 800-year-long tree-ring chronologies from multiple species better to understand the environmental conditions during the occupation and depopulation of the region.

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