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TREE-RING EVIDENCE FOR GREAT PLAINS DROUGHT

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ABSTRACT

A new collection of tree-ring chronologies developed from trees and remnant material located in the western and central Great Plains makes an important contribution to the spatial coverage of the US tree-ring chronology network. Samples from 24 sites were collected from the west-central Great Plains, and to date, ten chronologies have been produced. When correlated with a set of 47 single-station PDSI records, the chronologies display relationships with regional spring and summer drought. The reconstruction of spring PDSI for eastern Colorado generated in this study suggests that the inclusion of Great Plains trees can improve the quality of Great Plains drought reconstructions. The eastern Colorado drought reconstruction explains 62% of the variance in the instrumental record and extends to 1552. This reconstruction provides information about the regional character of major droughts over the past four and a half centuries. Major eastern Colorado droughts include events in the 1580s, 1630s, 1660s, 1730s, and the 1930s. The late 16th century drought, noted as an especially severe drought in the southwestern US, appears in this reconstruction as only slightly more severe than other major droughts in this region.

Keywords: drought, dendroclimatic reconstructions, PDSI, Great Plains, eastern Colorado.

DROUGHT AND THE GREAT PLAINS

The Great Plains region of the Unites States is prone to lengthy drought (Karl and Koscielny 1982; Diaz 1983). As the heartland for much of America's agriculture, this region is especially vulnerable to the socioeconomic impacts of drought. The Great Plains area has become increasingly vulnerable to drought because of an expansion of cultivation to marginally arable lands and a greater reliance on and consequent overuse of groundwater, which has resulted in depletion of aquifers in some areas (Lockeretz 1978; Hecht 1983). In addition, some General Circulation Models (GCMs) suggest the central United States, especially the Southern Plains, is likely to become hotter and drier with a doubling in atmospheric CO_2 resulting from anthropogenic activities, which may further increase vulnerability to drought (Rind *et al.* 1990; Wetherald and Manabe 1995; Houghton *et al.* 1996; Gregory *et al.* 1997; Wetherald and Manabe 1999).

Our capacity to evaluate the impacts of drought and plan for future droughts in the Great Plains is based almost entirely on our knowledge of droughts that have occurred during the period of

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instrumental record, *i.e.* the last 100 years. The droughts of the 1930s and 1950s are well-known for their severity, and had disastrous social and economic impacts in the Great Plains. These droughts are the standard by which others are gauged, but our ability to assess the rarity of these events is limited by the length of the instrumental record. However, the instrumental record can be lengthened using proxy climate data from historical documents, archaeological remains, tree rings, and geomorphological data that provide evidence of past Great Plains droughts. These proxy climate data can be used to place 20th century drought characteristics such as severity, duration, and frequency, in the context of the past centuries to millennia.

PALEOCLIMATIC RECORDS OF GREAT PLAINS DROUGHT

Of the proxy records that document Great Plains drought, the most recent come from historic documents and tree rings which provide information about drought occurrences for the past two to five centuries. A number of dendrochronological studies have utilized trees in areas flanking the Great Plains to reconstruct Great Plains precipitation and drought (Fritts 1983; Lawson 1974; Stockton and Meko 1983; Duvick and Blasing 1981; Blasing and Duvick 1984; Stahle *et al.* 1985; Stahle and Cleveland 1988; Cleaveland and Duvick 1992). Others have reconstructed climate for large areas that include the Great Plains (Fritts 1965, 1991; Stockton and Meko 1975; Cook *et al.* 1996, 1997, 1999). Most recently, Cook *et al.* (1996, 1997, 1999) reconstructed Palmer Drought Severity Indices (PDSI) (Palmer 1965) for a set of grid points across the US using a network of 425 tree-ring chronologies, enabling an assessment of the spatial patterns of drought for the past three centuries. These dendroclimatic studies, although employing chronologies from the periphery of the Great Plains, can provide information about Great Plains climate because tree growth often reflects large-scale climate patterns. A few studies have sampled trees within the Great Plains (Weakly 1943, 1965; Sieg *et al.* 1996), but these have not been used for actual drought reconstructions. The various tree-ring studies and reconstructions, along with historical data for the 18th and 19th centuries (Bark 1978; Lawson 1974; Muhs and Holliday 1995), suggest that although the droughts of the 1930s and 1950s were severe, they were not unusual in terms of their overall impact on the Great Plains region. Nation-wide, however, the 1930s drought was an unusual event because of its widespread extent.

Few tree-ring chronologies longer than 400 years in length exist to document Great Plains drought, but other less finely resolved or precisely dated longer records from lake and dune sediments are available. These records suggest more persistent or frequent periods of drought occurred in the past 2,000 years, than in the past century, that were severe enough to impact land cover and lake levels (Forman *et al.* 1992; Madole 1994; Laird *et al.* 1996, 1998; Muhs *et al.* 1996; Overpeck 1996; Fritz *et al.* 2000). Longer, high resolution tree-ring records of drought for regions outside the Great Plains support the evidence of drought in the less finely resolved Great Plains proxies (Douglass 1929; Dean *et al.* 1985; Dean 1994; Grissino-Mayer 1996; Hughes and Graumlich 1996; Stahle *et al.* 2000). These records document the occurrence of a number of multidecadal droughts in the western United States. The best documented and most recent of these occurred in the late 13th and late 16th centuries. There is evidence that the late 16th century drought (or several droughts within the second half of the 16th century) may have impacted regions from Mexico to British Columbia, and from California to the East Coast of the US (Stahle *et al.* 2000). There has been little evidence available to document this drought in the Great Plains, although one might suspect that such a drought-prone area would have experienced severe drought conditions as well.

Although these proxy records provide a general history of past droughts in the Great Plains, they do not provide much detail about the spatial patterns of drought across the Great Plains, nor do they provide much high-resolution temporal information about Great Plains drought prior to about 1650. In this paper, we report on a new network of tree-ring chronologies developed from trees and remnant material located in the western and central

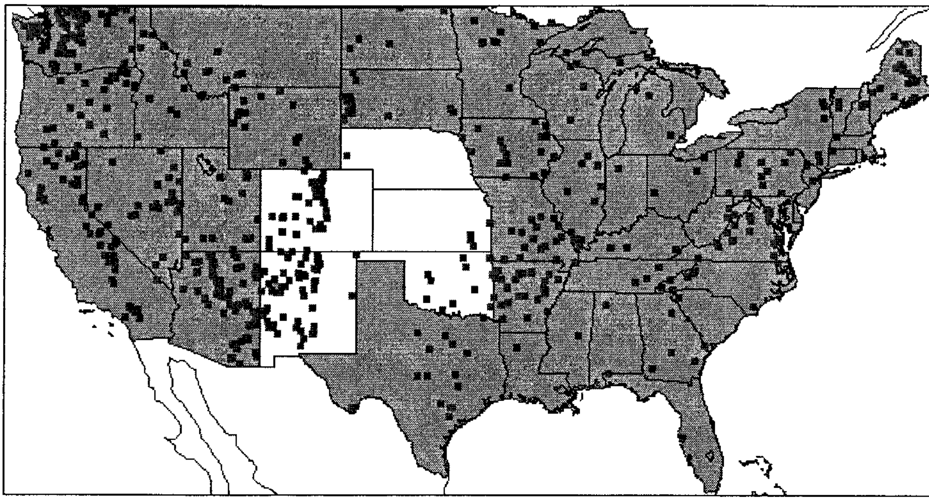

Figure 1. Locations of tree-ring chronologies in the coterminous US in the International Tree-Ring Data Bank. White area includes the Great Plains, where there is a noticeable lack of sites.

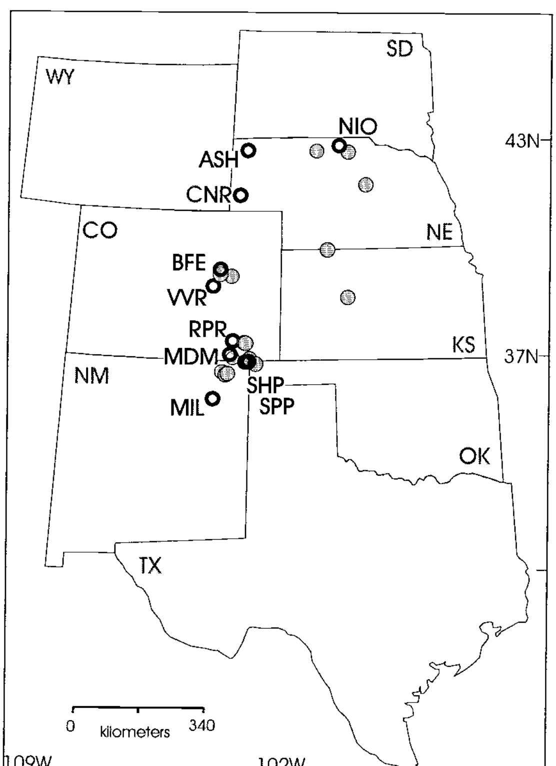

Figure 2. Locations of 24 new west-central Great Plains tree-ring collections. The sites for which chronologies have been generated are shown by black circles; the others by gray.

Great Plains that make an important contribution to the spatial coverage of the tree-ring chronology network (Figure 1). These new chronologies reflect regional responses to drought that can refine our understanding of the temporal and spatial patterns of drought in this region. In addition, several of the chronologies extend back into the 15th century and provide information about the character of the late 16th century drought in this region. We first describe the collection of new Great Plains chronologies, then examine individual chronology responses to regional drought conditions, and finally, report on a preliminary drought reconstruction for eastern Colorado.

NEW GREAT PLAINS TREE-RING CHRONOLOGIES

The New Network

Twenty-four new tree-ring chronologies were collected from central Nebraska to northeastern New Mexico (Figure 2, Table 1). In this part of the Great Plains, isolated stands of mostly ponderosa pine (*Pinus ponderosa*) and eastern red cedar (*Juniperus virginiana*) grow on scarps above rivers and drainages, and on isolated bluffs and mesas (Wells 1965). In the southern part of the study area, pinyon pine (*Pinus edulis*) is found along with ponderosa pine in sides of canyons and

Table 1. Great Plains dendrochronological collections and site details. Bold type indicates the chronologies generated to date.

Site Name	Site Code	Elevation (m)	Latitude/Longitude	Species
Nebraska				
Niobrara Valley Preserve	**NIO**	700–750	42°49′/100°00′	*Pinus ponderosa*
Snake River	SNA	800–820	42°42′/100°52′	*Pinus ponderosa*
Long Pine Creek	LGP	650–680	42°40′/99°43′	*Pinus ponderosa*
Jones Canyon	JON	680–700	41°48′/99°05′	*Pinus ponderosa*
Ash Creek	**ASH**	1260–1300	42°38′/103°15′	*Pinus ponderosa*
Canyon Road	**CNR**	1520–1540	41°31′/103°56′	*Pinus ponderosa*
Cedar Bluffs	CBN	790	39°58′/100°32′	*Juniperus virginiana*
Kansas				
Cedar Bluffs	CBK	670–680	38°46′/99°48′	*Juniperus virginiana*
Colorado				
Black Forest East	**BFE**	1790–1840	39°30′/104°13′	*Pinus ponderosa*
Limon	LIM	1740–1800	39°21′/103°48′	*Pinus ponderosa*
Limon	LIJ	1740–1800	39°21′/103°48′	*Juniperus scopulorum*
Ridge Road	RIR	1840–1850	39°23′/104°12′	*Pinus ponderosa*
Valley View Ranch	**VVR**	2150–2190	39°04′/104°26′	*Pseudotsuga menziesii*
Round Prairie	**RPR**	1590–1610	37°30′/103°32′	*Pinus edulis*
Kim	KIM	1640–1660	37°14′/103°15′	*Pinus ponderosa*
Kim Hill	KIH	1530	37°34′/103°18′	*Pinus edulis*
Mesa de Maya	**MDM**	1920–1940	37°06′/103°37′	*Pinus ponderosa*
Gotera Rincon	GOT	1900–1940	37°07′/103°05′	*Pinus ponderosa*
Sheep Pen Canyon	**SHP**	1570–1600	37°04′/103°16′	*Pinus ponderosa*
Sheep Pen Canyon	**SPP**	1570–1600	37°04′/103°16′	*Pinus edulis*
Myrtle Whitley's Ranch	MWR	1460–1520	37°00′/103°03′	*Pinus ponderosa*
Little Black Mesa	LBM	1430–1470	37°01′/102°58′	*Pinus ponderosa*
New Mexico				
Cornay Ranch	COR	2020	36°48′/103°59′	*Pinus ponderosa*
Capulin Volcano Ponderosa	CPP	2220–2260	36°46′/103°58′	*Pinus ponderosa*
Capulin Volcano Pinyon	CPI	2360–2400	36°46′/103°57′	*Pinus edulis*
Mill Canyon	**MIL**	1690–1740	36°04′/104°21′	*Pinus ponderosa*

on mesa tops. Trees such as cottonwood (*Populus sargentii*) and hackberry (*Celtis occidentalis*) are also found along waterways, but these are not usually as suitable for reconstructions because they tend to be short-lived.

Candidate tree-ring sites were located by examining maps for suggestive place names such as "Long Pine" and "Cedar Bluffs," air reconnaissance, and communication with local land managers, ranchers, and other long-time residents. Sites were selected on the basis of tree ages of several hundred years and the presence of remnant material, including stumps, logs, and snags. Many Great Plains trees were cut to supply forts established by the US Army in the 1840s–60s to protect emigrant wagon trains, commerce and the mail (West 1997). More were cut by the settlers who moved into the Great Plains in the second half of the 19th century. Fortunately, the semi-arid climate of this region preserves the stumps left from early settlement harvest, allowing an extension of the living tree chronologies back an additional two to four centuries.

The majority of the collections were from ponderosa pine because this species was among the most common, is sensitive to drought, attains ages of 300–400 years, and is relatively easy to date (fewer false rings than other species). The easternmost stands of ponderosa pine in North America extend just east of the 100th meridian in Nebraska and were included in our sampling. The westernmost extent of eastern red cedar is found in the western Great Plains. This species has not been previously sampled in this region, and it appears

Table 2. Statistics for standard chronologies.

Site Name	Site Code	Years	# of radii @ 1600	# of radii @ 1800	Mean Sensitivity	1st Order Autocor-relation	RBAR*
Nebraska							
Niobrara Valley	NIO	1589–1997	1	14	.217	.511	.466
Ash Creek	ASH	1716–1997	0	5	.232	.566	.409
Canyon Road	CNR	1489–1997	6	10	.287	.291	.400
Colorado							
Black Forest East	BFE	1709–1997	0	10	.259	.505	.509
Valley View Ranch	VVR	1537–1998	3	16	.550	.340	.602
Round Prairie	RPR	1743–1997	0	4	.365	.458	.615
Mesa de Maya	MDM	1464–1997	2	16	.327	.478	.535
Sheep Pen Canyon ponderosa	SHP	1460–1998	8	19	.376	.409	.634
Sheep Pen Canyon pinyon	SPP	1837–1998	0	0	.383	.129	.585
Cheesman L.**	CSM	1107–1995	8	15	.366	.315	.433
New Mexico							
Mill Canyon	MIL	1595–1998	1	20	.318	.255	.537

*RBAR is the average correlation between all possible time series calculated for 50 year segments, overlapped by 25 years, when sample size is ≥2.
**Cheesman is not a Great Plains chronology, but is listed here since it is used in the PDSI reconstruction.

to crossdate, but not easily (false rings are common). We sampled several stands of eastern red cedar in Kansas, but most of the living trees were not very old, and there was little remnant material available, although at one site, one extremely old individual was found (unfortunately rotten in the center). A ring count on a partial core from this tree yielded 462 rings, making this possibly the oldest tree in Kansas. One isolated stand of Douglas-fir (*Pseudotsuga menziesii*) was found and sampled. This stand is on the side of a bluff in the far eastern edge of the Black Forest region, 100 km southeast of Denver. Stands of ponderosa pine are common in this region, but, except for this stand, Douglas-fir is not found east of the foothills of the Front Range (Little 1971).

Regional Response to Drought

We investigated the drought signal contained in these Great Plains trees in order to assess the potential for reconstructing regional Great Plains drought. The strength and spatial extent of drought signals were examined by correlating tree growth at each chronology site with a set of single-station PDSI records for the west-central Great Plains, then mapping out the correlation patterns. The PDSI is a monthly index of drought which largely reflects precipitation, but also integrates the effects of temperature and local water content of the soil, as well as prior conditions (Palmer 1965; Guttman 1997). The PDSI was selected for these analyses because it reflects moisture from a water balance perspective, and thus more closely matches tree-growth response to drought than drought indices based solely on precipitation, such the Standard Precipitation Index (SPI, McKee *et al.* 1993; Edward Cook, personal communications).

Of the 24 collections, to date, tree-ring width chronologies have been generated for 10 sites, which were the basis for this analysis (Figure 2, Table 2). The 10 new chronologies were generated using standard crossdating and quality control techniques (Stokes and Smiley 1968; Holmes *et al.* 1986). Each chronology was correlated with a set of 47 single-station PDSI records in eastern New Mexico, Colorado, Wyoming and western Nebraska, Kansas, and Oklahoma, for the years

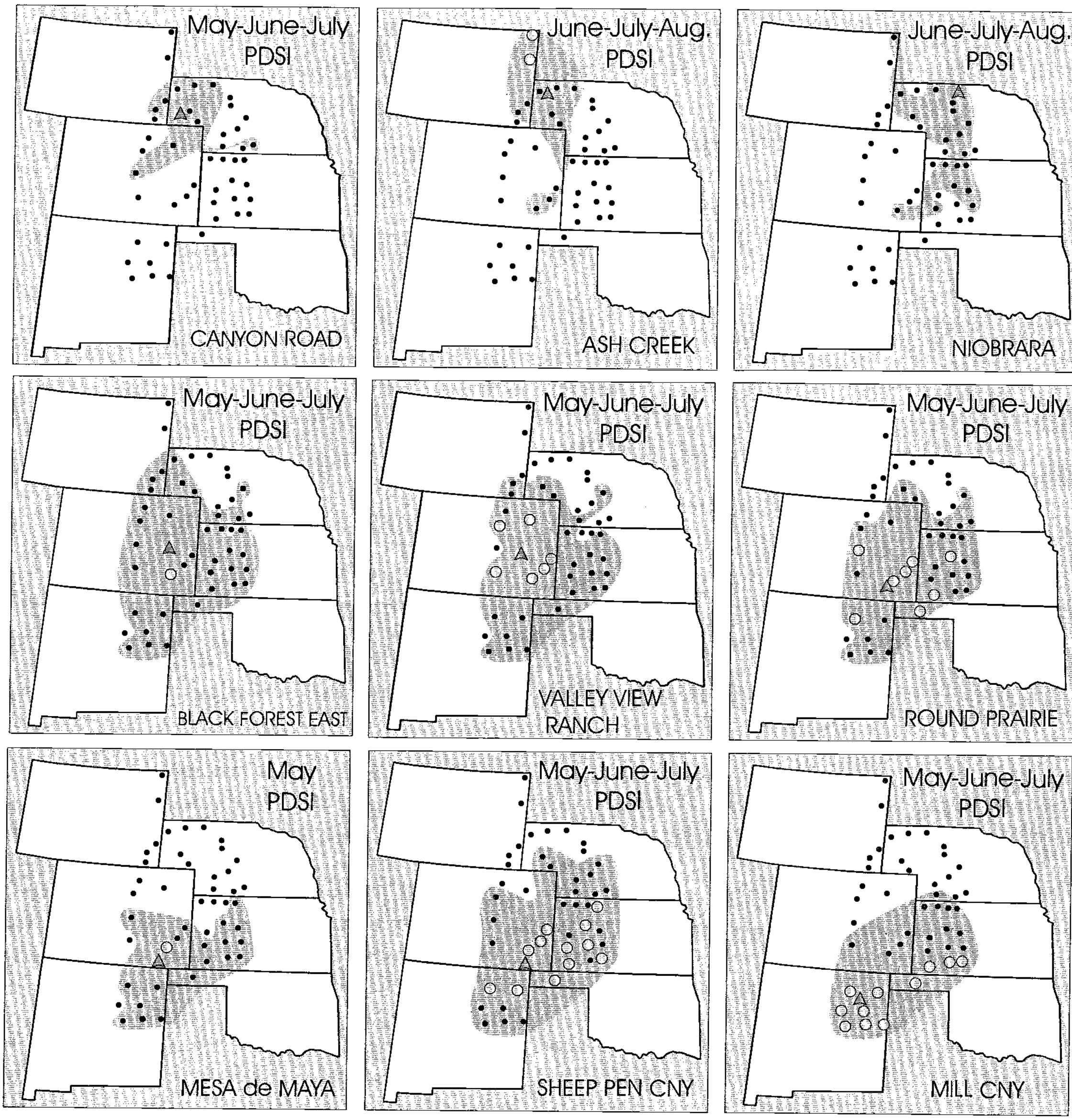

Figure 3. Maps of correlations between each chronology and the 47 PDSI station records, 1925–1990. Each map shows the locations of the PDSI stations (black and gray dots) and the tree-ring chronology (triangle). Maps are arranged to reflect to roughly relative geographic locations of the tree-ring sites. Tree-ring/PDSI station correlation values that are significant at $p < 0.01$ are included in shaded areas. Correlations where $r > 0.50$ are indicated by large gray dots. Maps are for the PDSI month or months of the highest correlations for each chronology (May, MJJ, or JJA).

1925–1990 (Figure 3). Climate stations were selected on the basis of record length and geographic extent of interest (central and western Great Plains). Station data were used instead of divisional climate data because climate divisions are based on factors other than climatology (*e.g.* watersheds, political boundaries). May PDSI, and May–June–July (MJJ) and June–July–August (JJA) average PDSI were selected for analysis with the chronologies because they are seasonally important for precipitation and tree-growth in this region, with the importance to growth grading from earlier months in the southern part of the study area to the later months in the northeast part. However, the three variables are very highly intercorrelated, since the PDSI has a built-in lag that reflects conditions in prior months (Palmer 1965).

Spatial patterns of correlations between each tree-ring chronology and the 47 station PDSI records show the sensitivity of tree growth to regional drought (Figure 3). Cutoff values used to delineate regional responses to drought were based on a significance level of $p < 0.01$ for one independent variable. This cutoff is not meant to imply statistical significance, since it does not take into consideration the problem of multiplicity, but is used as point of departure for this exploratory analysis. Months of the strongest correlations vary, with northeastern chronologies more sensitive to mid-summer PDSI. In general, correlations for each chronology show fairly spatially coherent relationships to regional PDSI. In the northern part of the study area, correlations are lower and tree growth is sensitive to drought in smaller regions than at the other sites. The easternmost chronology, Niobrara, has a central Nebraska/Kansas signature, while the two western Nebraska chronologies (Canyon Road and Ash Creek) key into drought conditions in western Nebraska and eastern Wyoming. The two central Colorado plains chronologies (Black Forest East and Valley View Ranch) have broader regions of drought sensitivity. Both have high correlations with neighboring eastern Colorado PDSI records, but also are correlated with PDSI records extending from southwestern Wyoming and southeastern Nebraska to central Kansas and northeastern New Mexico. The three southeastern Colorado chronologies (Round Prairie, Mesa de Maya, Sheep Pen Canyon) have similar patterns of correlations to the central Colorado chronologies, but areas of strongest correlations for Round Prairie and Sheep Pen are shifted to southeastern Colorado, southwestern Kansas, and northeastern New Mexico. The Mesa de Maya chronology has the most limited spatial signal of the three southeastern Colorado chronologies. Not shown are results for the pinyon pine chronology also generated at the Sheep Pen site. The spatial pattern of correlations for this chronology is quite similar to that of the Sheep Pen ponderosa pine chronology, but slightly less extensive.

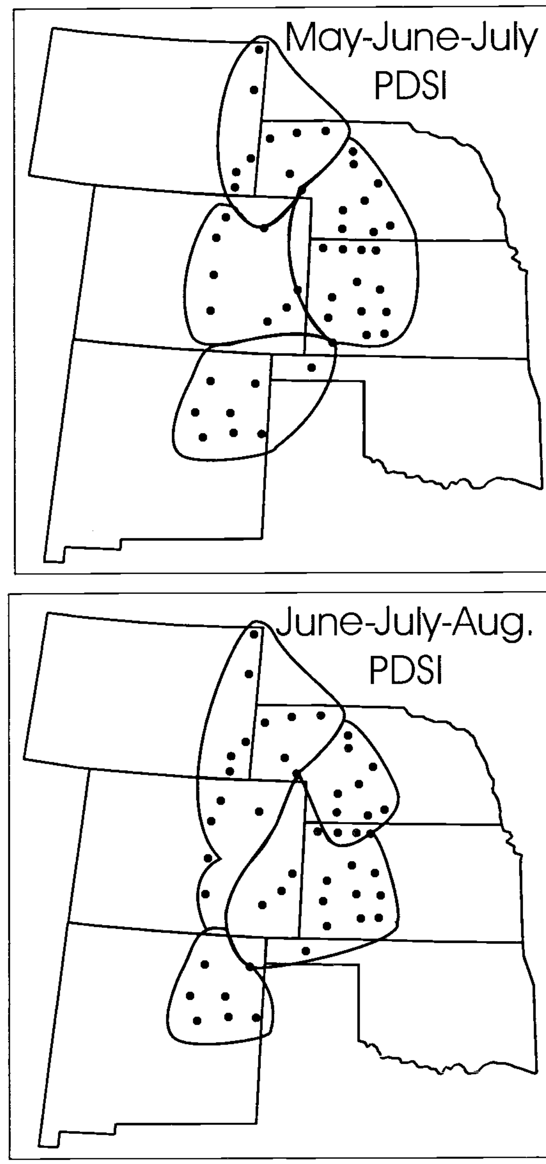

Figure 4. Spring/summer PDSI regions defined by RPCA (upper map, MJJ; lower map, JJA). PDSI stations are indicated by black dots. Regions are enclosed by outlines.

The regions represented by the chronology/drought correlation patterns reflect some of the main features of instrumental PDSI regions, defined by rotated principal components analysis (RPCA) (Figure 4). The RPCA was performed on the 47 station PDSI records averaged for MJJ and

JJA. Initially, eight components were retained, based on eigenvalues of 1.0 or greater. The eight PCs were subsequently reduced to four to facilitate the identification of broader drought regions. Although the regions vary somewhat for MJJ and JJA averages, especially in Colorado and Kansas, some features are similar for both. The split between northwestern and southwestern Nebraska remains consistent and is reflected in the correlation patterns for the Nebraska chronologies (Figure 3). Another fairly consistent feature is the northeastern New Mexico component. The pattern of highest correlations for PDSI and the Mill Canyon chronology, located in this region, reflects this component, with high correlations extending up into Oklahoma as does this component in the MJJ average. The correlation patterns for the central and southeastern Colorado chronologies reflect best the MJJ Colorado PDSI component, but several have broader drought signals, with strong correlations extending into the Kansas/Nebraska component (Round Prairie and Sheep Pen). Because these chronologies display fairly well-defined regional drought signals, they represent a good potential for reconstructing regional patterns of drought in the west-central Great Plains.

A DROUGHT RECONSTRUCTION FOR EASTERN COLORADO

A preliminary reconstruction of drought for eastern Colorado was undertaken on the basis of existing and newly generated long tree-ring chronologies and their correlations with regional PDSI. Besides the new long Great Plains chronologies, Valley View Ranch, Mesa de Maya, and Sheep Pen Canyon (ponderosa pine), three other long, precipitation-sensitive foothills chronologies were considered for the reconstruction, all extending prior to 1550. A new foothills chronology, Cheesman Lake (1107–1995), generated by co-author Peter Brown, was included, as well as two additional long chronologies from the World Data Center for Paleoclimatology's International Tree-Ring Data Bank (http://www.ngdc.noaa.gov/paleo/treering.html): Jefferson County (co539.crn, 1548–1987) and Eldorado Canyon (co533.crn, 1541–1987). All chronologies were generated from the

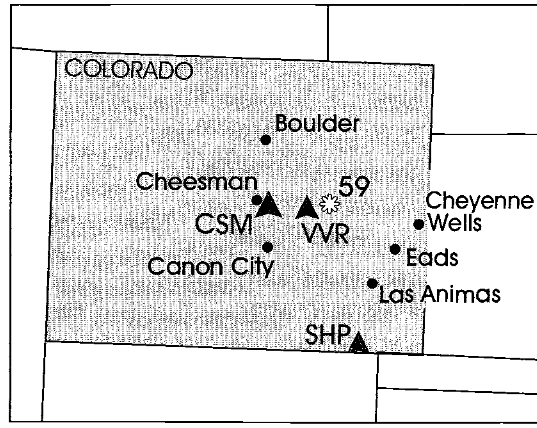

Figure 5. Locations of PDSI stations averaged for regional PDSI in eastern Colorado reconstruction (dots), chronologies in regression equation (triangles), and Grid point #59 from Cook *et al.* (1999) (star).

raw measurements using the software ARSTAN (Cook, 1985). The measurement series for each chronology were standardized using very conservative detrending methods to retain as much low frequency variation as possible (a stiff cubic spline or negative exponential curve). All of the chronologies contain positive autocorrelation, as indicated by one or more significant autocorrelation coefficients at low lags. Because such autocorrelation is probably due to biological rather than climatic factors (Fritts 1976), all chronologies were filtered with a low-order autoregressive-moving-average (ARMA) to remove significant autocorrelation at low lags.

Eastern Colorado is the area that best describes the most consistently strong correlations between tree growth in this set of chronologies and station PDSI. Six PDSI station records, Boulder, Cheesman, Canon City, Cheyenne Wells, Eads, and Las Animas, were used to define an eastern Colorado regional PDSI (Figure 5). This region also closely coincides with the MJJ Colorado PDSI region (Figure 4). The six station records were averaged to create a regional PDSI variable for late spring/summer (May–July). Five of the six station records began in 1902. The sixth, Eads, began in 1925. A comparison of the average of all six stations and the average of all stations but Eads, from 1925–1990, indicated a high degree of similarity (r = 0.991). Because of this result, and to obtain as

Table 3. Regression equation details.

Predictor Variable	Estimated Regression Coefficients	Standard Error	p-value (Significance of Estimated Regression Coefficient)
Sheep Pen Canyon ponderosa	3.564	0.752	0.000
Cheesman	1.870	0.699	0.011
Valley View Ranch	1.017	0.608	0.102
Constant	−6.503	0.851	0.000

Table 4. Calibration and verification statistics for Eastern Colorado MJJ PDSI reconstruction.

	Calibration Period (1902–1944)		Verification Period (1945–1987)	
r	0.785		0.737	
R^2	0.616		0.543	
$R^2_{adjusted}$	0.586			
RE			0.422	
CE			0.469	
Sign test	35/7 (hit/miss)		34/9 (hit/miss)	
	Observed	Reconstructed	Observed	Reconstructed
Mean	−0.057	−0.057	0.045	−0.103
Standard Deviation	2.096	1.645	2.027	1.526

long an instrumental record as possible, the instrumental record employed in the analyses used the average of the five stations from 1902–1924 and the average of all six stations from 1925–1990.

A stepwise regression, with the regional PDSI station record as the predictand and the six chronologies as the predictors, was used to generate a reconstruction model. The period of time common to both chronologies and the instrumental PDSI, 1902–1987, was split into two parts. The years 1902–1944 were used to calibrate the model, and the years 1945–1987 were used for model validation. Stepwise regression selected three variables, Sheep Pen Canyon, Valley View Ranch, and Cheesman Lake tree-ring chronologies (Figure 5), which explained 62% of the variance in the regional PDSI record (adjusted $R^2 = 0.59$; regression equation details are shown in Table 3). The residuals from the regression equation displayed no significant autocorrelation, trends, or correlation with predictor variables. Residuals were essentially normally distributed.

The regression model was then tested on the data for the independent verification period, 1945–1987. A standard suite of statistics (Fritts 1976; Cook and Kairiukstis 1990) was used to assess the predictive skill of the reconstruction (Table 4). The RE and CE statistics test the skill of the model in estimating values in the verification period, compared to estimates based on the mean of the observed data in the calibration (RE) or verification (CE) period (Lorenz 1956; Fritts 1976; Cook *et al.* 1999). RE and CE statistics can range from $-\infty$ to $+1$, with a positive value indicating that the model has some predictive skill. The sign test shows numbers of agreements/disagreements in sign of departure from the mean in the observed and reconstructed series.

Although a loss of explained variance occurs in the verification period (as is expected), the model still explains more than half of the variance in eastern Colorado PDSI in the independent verification period (Table 4). RE and CE statistics are both positive, indicating that the model has good predictive capability. Sign test results for both calibration and verification periods are significant ($\alpha = 0.01$). A comparison of the reconstructed and observed values shows that this model captures well the low PDSI (drought) conditions, but performs less well with the high PDSI (wet) values (Figure 6). This is a common problem that results from the lower sensitivity of trees to conditions that do not limit growth (*i.e.* wet conditions). The model does a particularly good job at duplicating

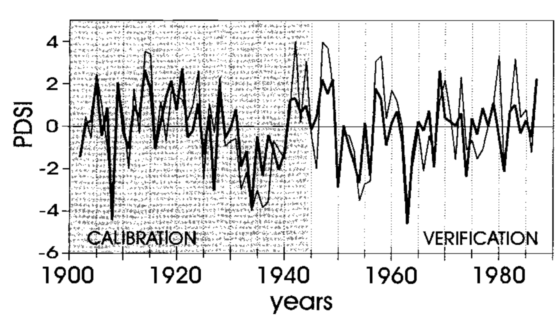

Figure 6. Observed (thin line) and reconstructed (thick line) MJJ PDSI for eastern Colorado. Calibration period is 1902–1944 (shaded) and verification period is 1945–1987.

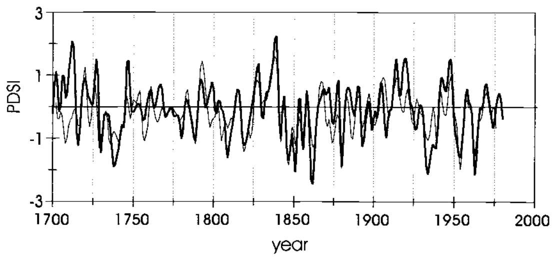

Figure 7. Comparison of eastern Colorado MJJ PDSI reconstruction (heavy line) and grid point #59 (east-central Colorado) JJA PDSI reconstruction (light line) from Cook *et al.* (1999), smoothed with a 5-weight binomial filter.

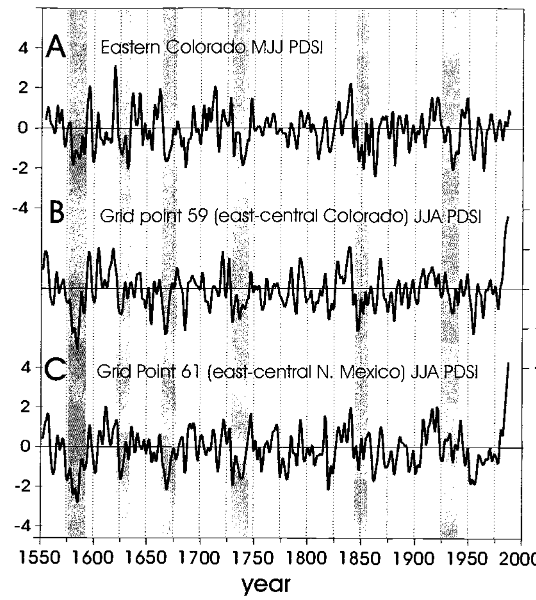

Figure 8. A. Reconstructed MJJ PDSI for eastern Colorado, 1552–1995. The line shows values smoothed with a 5-weight binomial filter. Shaded vertical bars indicate major droughts in this reconstruction. B. Reconstructed JJA PDSI for grid point #59 (east-central Colorado) (Stahle *et al.* 2000), shown here, 1550–1987. The line smoothing and shaded bars for eastern Colorado drought as in 8A. C. Reconstructed JJA PDSI for grid point #61 (east-central New Mexico) (Stahle *et al.* 2000), shown here 1550–1987. The line smoothing and shaded bars for eastern Colorado drought as in 8A.

The steep increase in PDSI in the latter part of the 20th century is a notable feature of the reconstructions for both grid points #59 and #61. It is not reflected in the instrumental record and is likely due to the anomalously warm and wet winters since the mid-1970s, conditions which appear to be especially favorable for growth in millennial-age Southwestern conifers (Swetnam and Betancourt 1998). New longer grid point PDSI reconstructions now available from WDC for Paleoclimatology (Cook *et al.* http://www.ngdc.noaa.gov/paleo/usclient2.html).

the 1930s drought, compared with previous Front Range reconstructions of precipitation and streamflow (Woodhouse 1999; Woodhouse 2001), perhaps because this drought is more marked in the eastern Colorado PDSI record than along the Front Range. The 1950s drought is well-replicated, as is the short, but severe 1963–1964 period of drought.

An alternative model was also developed and tested, using 1945–1978 (instead of 1902–1944) for the calibration period, and 1902–1944 as the verification period. Results were very similar, and though an excellent model also, some verification statistics were slightly lower than the model chosen for the reconstruction. A full time period model may capture slightly more of the instrumental record variability, but the model calibrated on years 1902–1944 was used because it is the model for which the calibration/verification statistics apply. The model was run on 30 year subperiods, overlapped by 15 years to assess the stability of the model over time. The multiple correlation values range from $r = 0.710$ to 0.826, indicating a good degree stability and no trend in correlations over time.

In the full reconstruction, 1552–1995, major 20th century droughts for this region (1930s, 1950s, and 1960s) can be compared to droughts of the past four and a half centuries (Figure 8a). The reconstruction reflects the widespread droughts (*e.g.* 1730s, around 1820, mid-1840s, and early 1860s) previously documented in other tree-ring reconstructions for the central and western United States (see references in Woodhouse and Overpeck 1998). Several of the reconstructed droughts appear to equal or exceed the 1930s drought in duration and severity, including the 1570s–1580s, 1660s, 1730s, and 1840s–1850s droughts.

COMPARISONS BETWEEN THE EASTERN COLORADO PDSI RECONSTRUCTION AND OTHER GREAT PLAINS RECONSTRUCTIONS

The statistical properties of the new reconstruction compare favorably with those for previous studies of central and western Great Plains drought or precipitation (Weakly 1943; Fritts 1983; Stock-

Table 5. Comparison of central and western Great Plains tree-ring records or reconstructions of drought or precipitation.

Study	Region	Calibration Period R^2
Weakly 1943	Western Nebraska	0.40
Fritts 1983	Central Great Plains	$0.20 \leq R^2 \leq 0.40$
Stockton and Meko 1983	E Wyoming, W Nebraska, SW South Dakota region	0.56
Cook *et al.* 1999	West/central Great Plains grid points	0.50–0.70
This study	Eastern Colorado	0.62

ton and Meko 1983; Cook *et al.* 1999). Squared correlations and explained variance (variance in the instrumental records explained by tree rings) reported for these prior studies range from 20% to 70% (Table 5). The explained variance in the new PDSI reconstruction falls at the high end of this range, at 62%.

The reconstruction most closely comparable with the eastern Colorado PDSI reconstruction, in terms of location, is the Cook *et al.* (1999) PDSI reconstruction of grid point #59, in east-central Colorado (grid point #59 instrumental and reconstruction data available from Paleoclimatology World Data Center; http://www.ngdc.noaa.gov/paleo/pdsi.html) (Figure 5). The two reconstructions are not directly comparable because different calibration and verification periods were used (#59 reconstruction calibration: 1928–1978; verification: 1895–1927; eastern Colorado reconstruction calibration period: 1902–1944; verification: 1945–1987). A more equitable comparison can be made using the eastern Colorado PDSI reconstruction based on a calibration period of the most recent years, 1944–1987, and verification period in the early part of the record, 1902–1944. Correlations between observed and reconstructed values for an early set of years (1902–1944) and a later set of years (1945–1978) for the two reconstructions are shown in Table 6. In both periods, the correlation values for the eastern Colorado PDSI reconstruction are somewhat higher than for the grid point #59 reconstruction. Other differences exist which prevent a strict comparison (different climate stations for the regional/grid point PDSI, and slightly different PDSI months for the seasonal average). However, these results suggest that the inclusion of Great Plains chronologies produces an improved estimate of PDSI in this area. Figure 7 shows the two reconstructions.

For years prior to 1700, only a few proxy records exist that reflect drought in the west-central Great Plains. In Weakly's (1965) western Nebraska chronology (1210–1958), periods of "reduced" growth considered to be droughts are reported that coincide with some droughts in the eastern Colorado PDSI reconstruction, including periods around 1630, 1670, and the 1930s (Table 7). The timing of drought in the late 16th century is somewhat later in the Weakly record than in the eastern Colorado reconstruction. Recently, the gridded

Table 6. Correlations between observed and reconstructed PDSI values for grid point #59 (east-central Colorado, Cook *et al.* 1999) and the eastern Colorado reconstructions.

	1945–1978	1902–1944
Grid point #59	0.772	0.576
This study	0.827	0.694

Table 7. List of 10 driest running 10-years sums of PDSI for eastern Colorado drought reconstruction (rank in parentheses; 1 = driest), and Weakly's (1965) list of periods with five or more years of reduced growth for same interval of time (1550s–1950s). Years in bold indicate droughts in both records.

Lowest 10-year PDSI Sums	Weakly's Reduced Growth Periods
1578–1587 (1)	1587–1605
1579–1588 (2)	**1626–1630**
1582–1591 (9)	**1668–1675**
1624–1633 (10)	1688–1707
1664–1673 (8)	1728–1732
1733–1742 (6)	1761–1773
1736–1745 (5)	1798–1803
1930–1939 (7)	1822–1832
1931–1940 (3)	1858–1866
1932–1941 (4)	1884–1895
	1906–1913
	1931–1940
	1952–1957

PDSI reconstructions of Cook *et al.* (1996, 1997, 1999) were recalculated to extend beyond 1700 (as originally generated), using a smaller network of longer tree-ring chronologies (Stahle *et al.* 2000). The new, longer PDSI reconstruction for grid point #59 (east-central Colorado) is shown (Figure 8b) along with the eastern Colorado PDSI reconstruction from this paper (Figure 8a). The extended grid point #59 reconstruction shows a more severe 16th century drought than the eastern Colorado PDSI reconstruction, as well as other differences, such as a more severe 1950s drought than the 1930s drought, and a marked increase in PDSI after the 1970s, which suggest a southwestern US drought signature (Figure 8c, grid point #61 for east-central New Mexico from Stahle *et al.* 2000). This difference may be due to the lack of long chronologies (the reconstruction extends to 1160) to draw from for this east-central Colorado grid point, and thus a greater reliance on longer, but more distant chronologies available in northern New Mexico. Both reconstructions do show droughts of similar magnitudes during the 1660s and 1730s. The eastern Colorado reconstruction shows more marked droughts during the 1620s, 1840s–1850s, and 1930s.

Results from the eastern Colorado drought reconstruction indicate that the 16th century event was a significant drought for this region. In ten-year running sums of reconstructed PDSI, periods in the last three decades of the 16th century rank as the driest (Table 7). However, this reconstruction, if it is representative of the central-western Great Plains region, suggests that the severity of late 16th century drought may not have been as exceptional as it is shown in reconstructions for the southwestern US (*e.g.* Grissino-Mayer 1996; Meko *et al.* 1995; Stahle *et al.* 2000) (Figure 8c for east-central New Mexico as an example). The eastern Colorado reconstruction during this period is based on ten trees (18 radii) from three sites and two different species, which does not represent a great sample depth, but does suggest that this is not a particularly isolated response. It is possible that these trees were some of the few survivors of an extended drought that decimated other populations, and that for some reason were less stressed by the drought, and thus survived. As we continue to develop more chronologies for the western Great Plains, we hope to obtain a better understanding of the nature of this drought in this region. If the drought is indeed less severe in this area than in the southwestern US, one possible reason for this difference is that annual ring widths of conifers in western US trees (at non-treeline sites) are commonly most highly correlated with winter moisture (Stahle *et al.* 2000), while trees in the central-western Great Plains appear to be more sensitive to spring and early summer moisture. It is possible that drought during the late 16th century resulted more from suppression of winter precipitation than from lack of late spring or summer precipitation.

One other source of long, high-resolution proxy records for Great Plains drought is lake sediments records. High sedimentation rates in some lakes in the northern Great Plains provide information on subdecadal-scale climate variability, but fine-scale variations are difficult to match between records because of the dating error inherent in radiocarbon dating (± at least 50 years) (Fritz *et al.* 2000). Differences in local climate or in lake-specific hydrologic responses to climate forcing contribute to this difficulty. However, a collection of sediment records from three lakes in eastern and central North Dakota that reflect hydrologic variability do show evidence of drought around 1600, with comparable droughts around 1750 and the last half of the 19th century (Fritz *et al.* 2000).

SUMMARY

Recent field work has yielded 24 new dendrochronological collections in the west-central Great Plains. The collections demonstrate the possibility of expanding the tree-ring chronology network into areas where trees are not abundant or long-lived, but which contain a wealth of remnant material. Ten chronologies have been generated from these collections, to date, and at least nine more will eventually be produced. Of the ten so far, six extend into the 16th century, two of these into the 15th century, and one which is currently in progress promises to extend into the 14th century.

The west-central Great Plains tree-ring chronologies are correlated with spring and summer PDSI.

Correlations between individual chronologies and a set of 47 single-station PDSI records show that drought signals are strongest and most widespread in eastern New Mexico and Colorado, but distinctive regional drought signals are also evident in the Nebraska chronologies. These results suggest good potential for reconstructions of regional PDSI which may be useful for investigating patterns of drought across the Great Plains.

A preliminary reconstruction of MJJ PDSI for part of eastern Colorado, 1552–1995, was produced using two new Great Plains chronologies and one foothills chronology. The reconstruction model explains 62% of the variance in the regional instrumental PDSI record, and is well-validated with independent data. Comparisons of this reconstruction with existing reconstructions of Great Plains drought suggest that incorporating Great Plains chronologies contributes to the quality of Great Plains drought reconstructions. The reconstruction also provides new information about the impact of the late 16th century drought in this region, which may have been less severe than in the southwestern US. Future work will further investigate spatial and temporal characteristics of drought in eastern Colorado and in other parts of the west-central Great Plains.

The importance of drought studies in this area cannot be underestimated. The region covered by this reconstruction includes the heavily populated Front Range metropolitan area as well as agricultural areas of the western Great Plains. The state of Colorado, the southeastern part in particular, has experienced above-average precipitation for much of the last two decades (McKee *et al.* 1999). Tremendous growth in urban areas has occurred over this time and water has become an extremely important commodity. Many volatile water issues related to growth have emerged, such as the transfer of water rights from agricultural areas and the assessment of the value of water (Frasier 2000). Periods of drought will only exacerbate these issues. The dendroclimatic record of drought indicates that drought has been a regular feature of this region, and will undoubtably be continue to be so.

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