DENDROCLIMATIC POTENTIAL IN THE NORTHERN GREAT PLAINS

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Abstract. We evaluate the potential for dcndroclimatological reconstruction in the northern Great Plains of the United States, based on a newly developed network of 23 chronologies of bur oak *(Quercus macrocarpa)*, ponderosa pine *(Pinus ponderosa)* and Rocky Mountain juniper (Juniperus *scopoulorum)* from North Dakota, South Dakota and Iowa. Earliest dates of specimens are AD 1281 for pine, 1597 for juniper, and 1676 for oak. The mean between-tree correlations of ring-width indices at the various sites range from 0.33 to 0.57. Computed values of the expressed population signal indicate that the number of trees sampled is adequate to capture the theoretical common-growth signal at 13 of the 23 sites. Correlations between tree-ring series and precipitation are higher on most sites for annual precipitation than for spring and summer precipitation, suggesting that ring-width variations reflect moisture conditions integrated over seasons. The 12-month grouping yielding highest precipitation-tree ring correlations is September of the previous year through August of the growth year. Sites with relatively high precipitation signals were found for each species, but a decrease in sample size for earlier years generally limits the period of reliable climatic inference from the widely distributed oak chronologies to the mid-1800s. The period of reliable inference for the western Dakotas (from pine and juniper) extends to the early 1600s, and could probably be extended to carlier centuries with additional collection.

Introduction

General circulation models predict that summer soil moisture in the northern Great Plains will decline under co_2-induced warming (Manabe and Wetherald 1986). Tree-ring data can be used to factor natural climate variability into such predicted declines. Tree-ring studies aimed at documenting the drought history of the Great Plains have been hindered by a lack of tree-ring chronologies owing to the scarcity of trees in the central parts of the Plains (Stockton and Meko 1983; Meko 1992). Low precipitation, severe winters, high evapotranspiration rates and recurring droughts in the northern Great Plains restrict the growth of trees to ravines and floodplains or to areas of increased elevation that receive additional moisture; these factors, combined with the demands of early settlers for wood, contribute to the difficulty of finding old trees (Albertson and Weaver 1945).

The climate of the northern Great Plains is semiarid and continental (Omodt et *al.* 1968). Extensive snow accumulation is uncommon except in the northern Black Hills. Most precipitation falls from April through September. Summer rainfall is sporadic and characterized by intense thunderstorms. Annual precipitation for the region ranges from 356 to 711 mm (14-28 in.) (Owenby and Ezell 1992). The greatest amounts are confined to the northern Black Hills and extreme eastern South Dakota. Periodic seasonal and yearly droughts are common.

Tree species that occur within part or all of this region and show some promise for use in climatic reconstructions include ponderosa pine (*Pinus ponderosa),* Rocky Mountain juniper *(Juniperus scopulorum),* eastern redcedar *(J. virginiana),* and bur oak (*Quercus macrocarpa).* Ponderosa pine is limited to the' western portion of the study area. Rocky Mountain juniper occurs in the western Dakotas; eastern redcedar is more common to the east of the Missouri River; and hybrids of the two

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species are found where their ranges overlap (Noble 1990). Ponderosa pine can be long-lived and climatically sensitive, and has been applied in drought studies along the western edge of the Plains (Stockton and Meko 1983). Eastern redcedar has been used in studies of drought in Oklahoma (Butler and Walsh 1988) and Nebraska (Weakly 1943). The sensitivity of Rocky Mountain juniper to climatic variability is unknown. Bur oak occurs throughout the study area, tends to live longer than many other deciduous species (Johnson 1990), and has been used for climatic inference in North Dakota (Will 1946) and eastern Nebraska (Lawson *et al.* 1980).

METHODS

We collected tree-ring samples from 53 separate sites in the Dakotas and Iowa in 1991 and 1992, with the goal of developing a widely distributed network of long, climatically sensitive chronologies. Site descriptions and details of the chronology development can be found elsewhere (Meko and Sieg 1995). In this paper, we summarize statistical properties of 23 chronologies developed so far (Fig. 1), focusing on properties relevant to climate reconstruction: chronology length, sample depth (number of trees), consistency of tree-ring patterns among trees, and correlation between tree-ring series and precipitation.

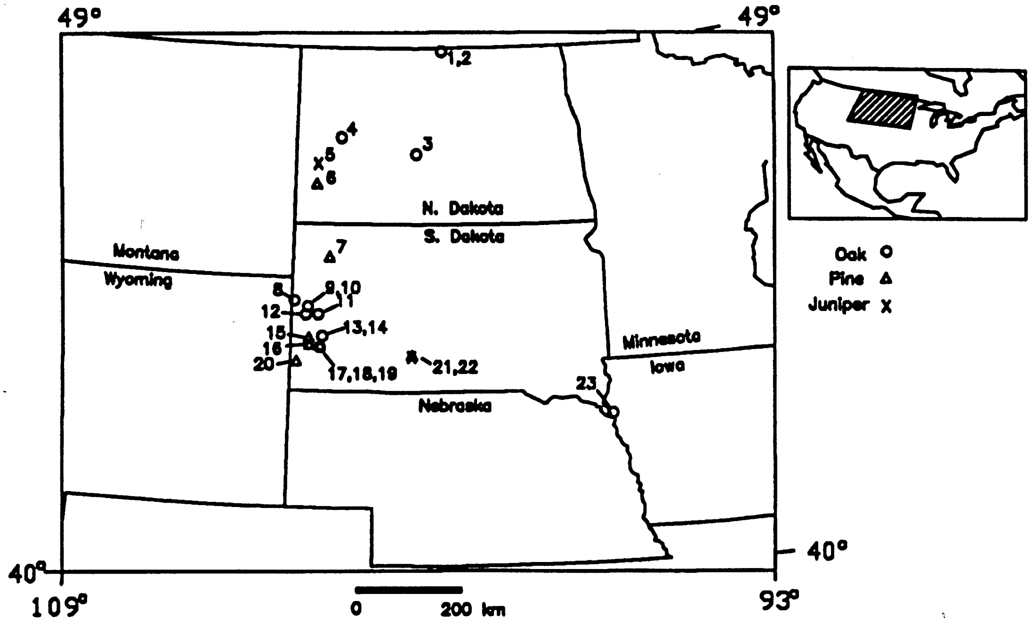

Fig. 1. Sample site distribution, by tree species, of 23 chronologies collected from the northern Great Plains of the United States in 1991–1992.

Potential study sites included areas of increased elevation, isolated stands of ponderosa pine and Rocky Mountain juniper, preserves, research areas, and State and National Parks. We also relied on suggestions from land owners and managers. At each site, an effort was made to sample trees on drier slopes (south- or southwest-facing). Our goal was to sample a minimum of 20 trees per site. Two cores were taken at waist height from opposite sides of each tree with an increment borer, and sample ring widths were crossdated and measured by standard techniques (Stokes and Smiley 1968) at the Laboratory of Tree-Ring Research in Tucson, Arizona. Computer software based on lagged cross-correlations between pairs of ring-width series was used as an aid to flagging possible dating and measuring errors (Holmes 1983; Grissino-Mayer, Holmes and Fritts 1992).

Ring-width series were detrended using cubic smoothing splines with a 50% amplitude frequency response at two-thirds the sample length; these criteria ensure that information on low-frequency climatic variation is not unnecessarily lost in estimating and removing the growth trend (Cook and Kairiukstis 1990). Standard chronologies (those with the effects of increasing age on ring width removed) and residual chronologies (those with the carryover effect from previous years' growth also removed) were derived using the ARSTAN computer program for tree-ring standardization (Grissino-Mayer, Holmes and Fritts 1992).

We measured the internal consistency of tree-ring variations at a site by the mean between-tree correlation $\overline{r_{bt}}$, or the average correlation coefficient between core indices from different trees (Cook and Kairiukstis 1990). We then calculated the expressed population signal (EPS), which is a measure of how well a chronology based on a finite number of trees approximates the theoretical population chronology (Cook and Kairiukstis 1990: 149), and is computed by the formula

$$EPS = \frac{\overline{r_{bt}}}{\overline{r_{bt}} + (1 - \overline{r_{bt}})/t} \tag{1}$$

where t is the number of trees in the sample.

The subsample signal strength (SSS) addresses the related question of how representative a t' tree chronology (subsample) is of a t tree chronology (sample). Reconstruction models are typically calibrated on the most recent part of a chronology, and are used to infer climate variations in earlier years. Because sample size (number of trees) typically drops off with increasing time, the SSS is a convenient measure for identifying the period for reliable application of a reconstruction (Cook and Kairiukstis 1990). The formula for SSS is:

$$SSS = \frac{EPS(t')}{EPS(t)} \tag{2}$$

where t' is the number of cores in a subsample, and t is the number of cores in the sample.

An EPS of 0.85 was used as a guideline for identifying the cutoff year before which sample size is too small to capture the theoretical "population" signal of tree-ring variation at the site (Wigley, Briffa and Jones 1984). An SSS of 0.85 was used to identify the year before which sample size is too small to capture the signal represented in the "full" sample from the later part of the record.

The strength of the precipitation signal in the tree-ring chronologies for the common period 1919–1989 was summarized by the product-moment correlation coefficient between each residual chronology and both spring/early summer (April–July) and 12-month-total precipitation averaged over nearby climatic stations from the Historical Climate Network (Quinlan, Karl and Williams 1987). For this analysis, monthly precipitation series paired with each tree-ring site were generated by averaging over the nearest (up to three) Historical Climate Network stations within a search radius of 100 km. The importance of April–July precipitation to tree-ring variations in the study area was suggested by a previous correlation analysis of a subset of our tree-ring series and monthly temperature, precipitation, and Palmer Drought Severity Index (Ni 1993). We extended the April–July correlation analyses to all the tree-ring sites and examined correlations for various 12-month periods with ending months ranging from March to November of the growth year.

RESULTS AND DISCUSSION

The study area encompasses North and South Dakota and the extreme northwestern corner of Iowa (Fig. 1). Relatively old trees were concentrated in the western portion of the study area; only a few trees sampled in central or eastern South and North Dakota were >150 yr old. Site distribution is given in Table 1.

TABLE 1. Beginning year in standard chronology and number of trees in chronologies beginning in 1800, 1850, and 1900, by state, region and tree species, for northern Great Plains chronologies, 1991–1992.

Site	Site no.	Latitude (°N)	Longitude (°W)	Tree species	First year	No. trees in chronology beginning		
						1800	1850	1900
North Dakota								
North central								
Masonic Island	1	48°59′	100°20′	Oak	1676	1	3	3
Bear Island	2	48°59′	100°21′	Oak	1782	0	3	4
Central								
Cross Ranch	3	47°9′	101°1′	Oak	1788	2	5	6
Western								
Kildeer Mtns.	4	47°25′	102°55′	Oak	1777	2	8	13
Theodore Roosevelt NP	5	46°55′	103°29′	Juniper	1597	14	16	17
Burning Coal Vein	6	46°36′	103°28′	Pine	1592	18	18	19
South Dakota								
Northwest								
Eagles Nest Canyon	7	45°21′	103°8′	Pine	1651	13	17	18
Northern Black Hills								
Thompson Ranch	8	44°35′	104°0′	Oak	1747	1	1	3
Frawley Dairy Farm	9	44°28′	103°40′	Oak	1807	0	2	5
Frawley	10	44°29′	103°41′	Oak	1858	0	0	3
Blair Ranch	11	44°20′	103°26′	Oak	1751	4	5	8
Hankins	12	44°20′	103°41′	Oak	1733	0	0	7
Central Black Hills								
Crystal Cave	13	43°57′	103°18′	Oak	1833	0	1	5
Rockerville	14	43°56′	103°22′	Oak	1717	3	3	5
Reno Gulch	15	43°54′	103°36′	Pine	1281	12	12	12
Southern Black Hills								
Buckhorn Mtn.	16	43°47′	103°36′	Pine	1600	6	8	9
Grace Coolidge	17	43°45′	103°21′	Oak	1767	2	6	14
Grace Coolidge	18	43°45′	103°21′	Pine	1703	4	8	9
Custer State Park	19	43°45′	103°23′	Oak	1775	4	5	4
Pilger Mtn.	20	43°30′	103°53′	Pine	1646	4	5	5
South Central								
Cedar Butte	21	43°36′	101°7′	Pine	1646	6	8	9
Cedar Butte	22	43°36′	101°7′	Juniper	1691	1	2	6
Iowa								
Stone State Park	23	42°33′	96°28′	Oak	1796	1	2	11

A total of 23 chronologies were developed, including 7 from ponderosa pine, 14 from bur oak, and 2 from Rocky Mountain juniper. The earliest dated year of any tree in a chronology ranges from AD 1281 to 1703 for ponderosa pine, AD 1676 to 1858 for bur oak, and AD 1597 to 1691 for Rocky Mountain juniper (Table 1). Sample size, as measured by number of trees, is stable since *ca.* 1800 for the pine and juniper chronologies, but drops off sharply with time before 1850 for oak. The standard chronology begins with the earliest dated year, except at 6 sites for which the earliest rings were truncated for various reasons (e.g., juvenile growth period, weak crossdating).

The average between-tree correlation of residual core indices in common periods ranges from 0.36 to 0.57 for ponderosa pine, 0.33 to 0.57 for oak, and 0.50 to 0.51 for juniper (Table 2). These correlations and the change in sample size determine the change of the EPS with time. The EPS ultimately reaches 0.85 at 13 sites (Table 2). The threshold of 0.85 is reached in the 1600s or 1700s for 5 of 7 pine chronologies, and in the 1700s or 1800s for the juniper chronologies. The threshold is not reached until the 1800s or 1900s, if at all, for the oak chronologies. Collection of additional old trees at the oak sites or nearby locations is required for reliable tree-ring information much beyond the period overlapped by instrumental weather records. The strongest chronology as measured by EPS is the pine site Burning Goal Vein in western North Dakota. The earliest date of any core in this chronology is *1592; EPS* reaches 0.85 in 1630. Additional collection at a site such as this would be of only marginal value because the “population” signal has already been approximated.

TABLE 2. Average between-tree correlation coefficients of residual core indices in common periods, and year in which expressed population signal(EP) and subsample signal strength (SSS) reach 0.85, for northern Great Plains chronologies, 19914992.

Tree species Site	Site no.	Common period	No. trees	Between-tree correlation*	Year EPS reaches 0.85	Year SSS reaches 0.85
Bur oak						
Masonic Island, ND	1	1861-1990	3	.47	never**	1834
Bear Island, ND	2	1862-1988	3	.46	never	1801
cross Ranch, ND	3	1909-1990	8	.41	never	1825
Kildeer Mtns., ND	4	1911-1990	15	.47	1820	1809
Thompson Ranch, SD	8	1913-1990	4	.56	never	1882
Frawley Dairy Farm, SD	9	1896-1990	6	.51	1895	1864
Frawley, SD	10	1914-1990	3	.57	never	1895
Blair Ranch, SD	11	1880-1990	5	.50	never	1769
Hankins, SD	12	1901-1990	5	.35	never	1877
Crystal Gave, SD	13	1909-1990	8	.41	1904	1893
Rockerville, SD	14	1901-1990	5	.33	never	1897
Grace Coolidge, SD	17	1891-1990	9	.47	1853	1802
Custer State Park, SD	19	1796-1989	4	.42	never	1794
Stone State Park, IA	23	1898-1990	11	.48	1872	1864
Ponderosa pine						
Burning Coal Vein, ND	6	1807-1983	18	.53	1630	1630
Eagles Nest Canyon, SD	7	1864-1990	16	.51	1701	1687
Reno Gulch, SD	15	1794-1990	12	.38	1745	1613
Buckhom Mtn., SD	16	1785-1990	17	.49	1655	1655
Grace Coolidge, SD	18	1841-1986	6	.50	1814	1774
Pilger Mtn., SD	20	1833-1971	5	.36	never	1710
Cedar Butte, SD	21	1845-1991	8	.57	1675	1675
Rocky Mountain juniper						
Theodore Roosevelt NP, ND	5	1897-1990	12	.51	1729	1684
Cedar Butte, SD	22	1857-1973	6	.50	1854	1827

*All correlation coefficients significant ($P < 0.05$)

**EPS always < 0.85

Previous dendroclimatic studies in the northern Plains have indicated that ponderosa pine tree-ring series integrate drought conditions over seasons, and that a reasonable "annual" grouping for capturing the climate signal is the previous September through August of the growth year (Meko 1982; Stockton and Meko 1983). The mean correlations between residual tree-ring indices and various 12-month groupings of precipitation for the 23 chronologies support the choice of September-August as an annual drought window for ponderosa pine and bur oak, and suggest that this window is probably also reasonable for juniper (Fig. 2). The results for juniper are tentative, however, as the mean correlation is based on only two chronologies. The September-August correlation (r = 0.62) was only slightly lower than the July-June correlation (r = 0.64) for one of these juniper chronologies (site 22 in Table 1).

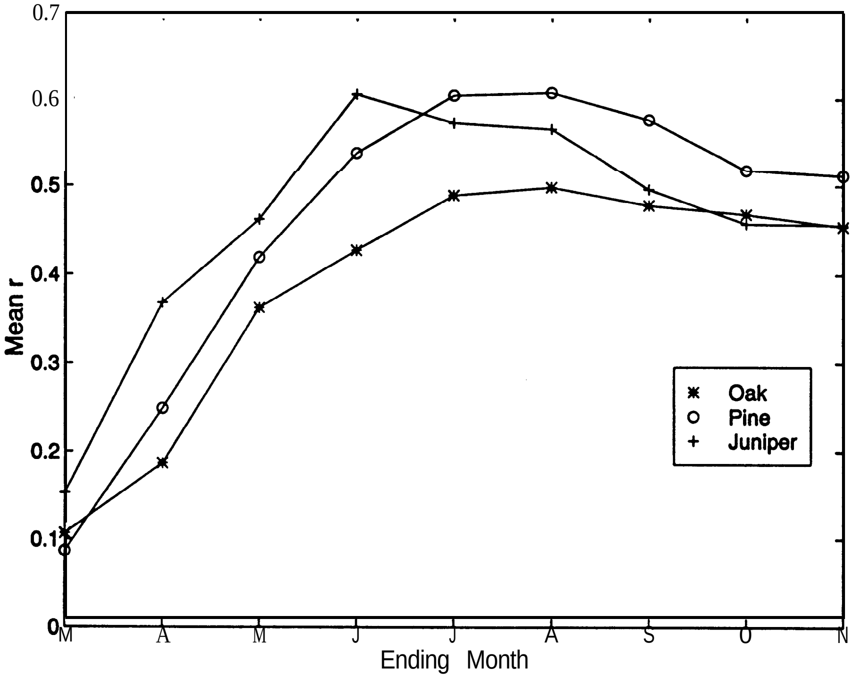

Fig. 2. Mean correlations between annual precipitation and residual tree-ring chronologies for different species and 12-month groupings of precipitation. Ending month of 12-month periods ranges from March of growth year (far left) to November of growth year (far right). Period for analysis: 1919-1989.

With the exception of three sites from the northern part of the study area, tree-ring indices were more highly correlated with total annual precipitation than with April through July precipitation (Fig. 3). Correlation coefficients between pine chronologies and precipitation range from 0.54 to 0.70 for total annual precipitation, and from 0.49 to 0.66 for spring precipitation. The highest pine correlation coefficients were obtained for the southwestern North Dakota site. The range of correlation coefficients is greater for bur oak: from 0.36 to 0.69 for annual total, and from 0.31 to 0.63 for spring precipitation. The lowest oak coefficients were obtained for both north-central North Dakota sites and two Black Hills sites; the highest coeffients for both spring and annual precipitation were found at the Grace Coolidge site in the southern Black Hills. Correlation coefficients for the two Rocky Mountain juniper sites were 0.52 and 0.62 for annual precipitation and 0.47 and 0.59 for spring precipitation. The highest correlations for the three species are comparable to tree-ring climate correlations reported for climatically sensitive chronologies in other parts of the western United States (Schulman 1956).

An SSS of 0.85 was arbitrarily used to identify the year before which these climate correlation coefficients become unrepresentative because of decreasing sample size (Table 2). The threshold of 0.85 is reached in the 1600s or 1700s for the pine chronologies, but not until the late 1700s, 1800s or early 1900s for the oak chronologies. For Rocky Mountain juniper, the 0.85 threshold is reached in the 1600s at one site and the 1800s at the other. The strongest chronology as measured by SSS is the pine site Reno Gulch in the central Black Hills of South Dakota. The earliest date of any core in this chronology is 1281; SSS reaches 0.85 in 1613.

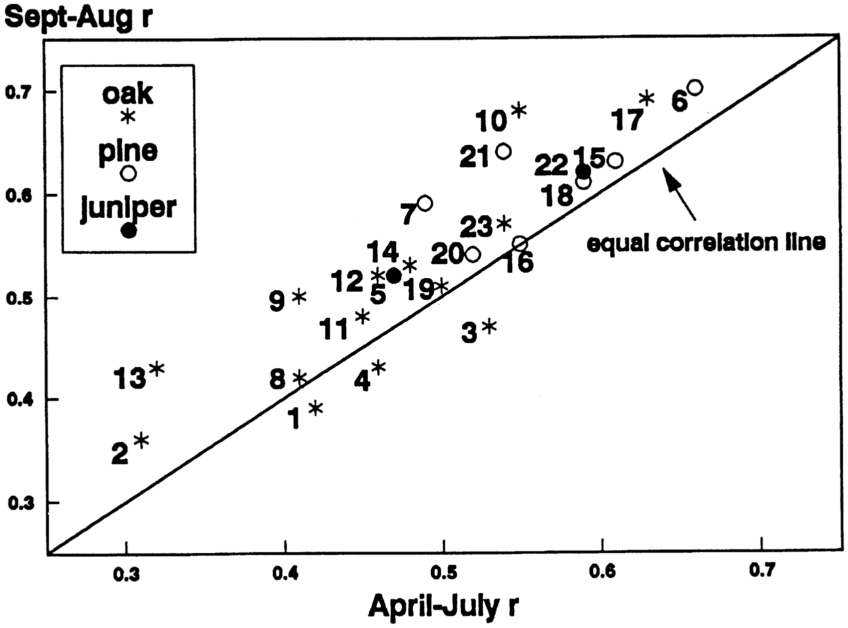

Fig. 3. Correlation coefficients (r) between tree-ring chronologies and annual (Sept.–Aug.) precipitation (Y axis), and April-July precipitation (X axis), for 23 northern Great Plains sample sites, by tree species. All correlation coefficients are significant ($P < 0.05$). Sites above the equal correlation line are those where the correlation between tree-ring widths and annual precipitation is stronger than the correlation with April–July precipitation; and sites below the line are those where the correlation is stronger with April–July precipitation than with annual precipitation. Period for analysis: 1919–1989.

CONCLUSION

The results of our field research and statistical analyses to date suggest that the greatest potential for multi-century dendroclimatic reconstructions from trees in the northern Great Plains is limited to the western part of the Dakotas, and that efforts there are most likely to be successful if concentrated on ponderosa pine and Rocky Mountain juniper. Both species were found to crossdate well, to give time coverage predating AD 1600 (1281 for pine), and to yield relatively high correlations with precipitation. The dendroclimatological potential of bur oak is excellent on some sites if the time period of interest is restricted to post-1800. The wide spatial distribution of bur oak and the high correlation of some oak chronologies with precipitation are promising for climatological and ecological studies requiring sub-regional spatial resolution within the northern Great Plains.

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