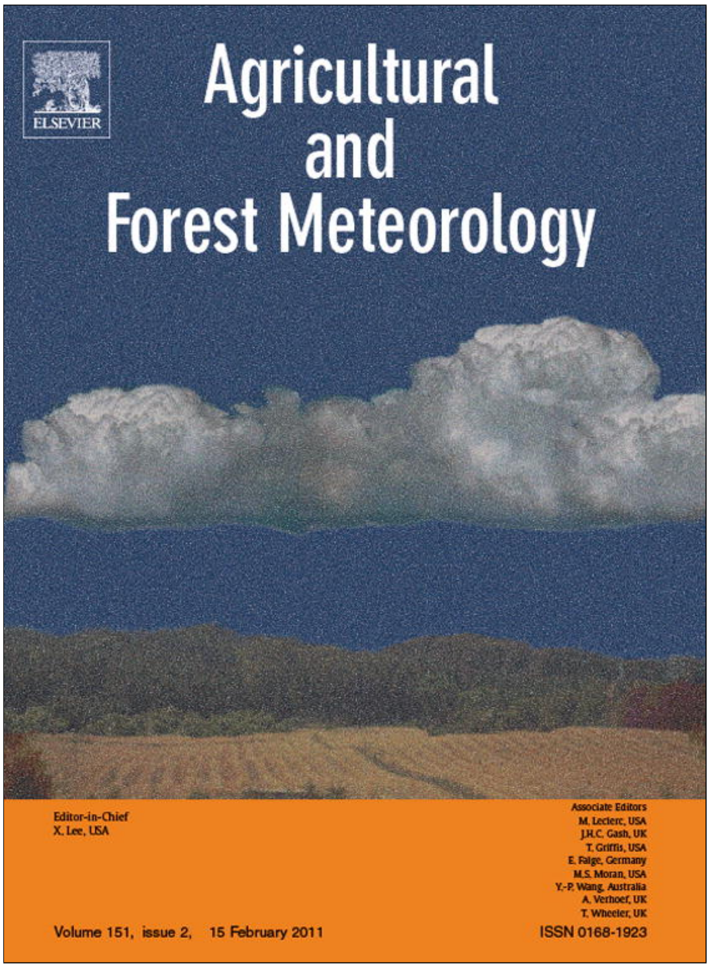
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Drought duration and frequency in the U.S. Corn Belt during the last millennium (AD 992–2004)

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ABSTRACT

Drought is among the most costly natural hazards affecting the United States, averaging $6 to $8 billion annually in damages, primarily in crop losses. Mitigating the impacts of drought through planning and preparedness has the potential to save billions of dollars. We used a new long tree-ring chronology developed from the central U.S. to reconstruct annual drought and characterize past drought duration, frequency, and cycles in the U.S. Corn Belt region during the last millennium. This is the first paleoclimate reconstruction achieved with subfossil oak wood in the U.S. and increases the current dendroclimatic record in the central U.S. agricultural region by over 500 years. A tree ring-width drought response function was calibrated and verified against monthly instrumental Palmer Hydrologic Drought Index (PHDI) during the summer season (JJA). Separate reconstructions tailored to emphasize high-frequency and low-frequency variations indicate that drought conditions over the period of instrumental records (since 1895) do not exhibit the full range of variability, severity, or duration of droughts during the last millennium. For example, three years in the last millennium were drier than 1934, a classic Dust-Bowl year and the driest year of the instrumental period. Thirteen decadal to multidecadal droughts (i.e., ≥10 years) occurred during the last millennium – the longest lasting sixty-one years and centered on the late twelfth century. Reconstructions exhibited quasi-periodicity at bidecadal and century-scale periods. Significant rhythms in drought were identified near 20-yr and 128-yr periods. The tree-ring drought reconstruction shows promise in providing new information about long-term climate variability in the agricultural regions that could potentially span multimillennia. We postulate that tree-ring chronologies (i.e., tree growth), thus far under-utilized in agricultural applications, have the potential to match contributions of instrumental climate data.

1. Introduction

The linkages between agriculture and climate are complex and marked with economic consequence. Drought is among the most costly natural hazards affecting the United States, averaging $6 to $8 billion annually in damages, primarily in crop losses (FEMA, 1995). This estimate does not even include indirect and societal costs, such as detriment to public water supplies, recreation and tourism, and natural ecosystem services (Wilhite et al., 2006), making the true economic impact of drought much higher. Previous prolonged North American droughts have resulted in serious societal difficulties such as famine, disease, unemployment, land tenure, and political unrest (Acuña-Soto et al., 2002; Therrell et al., 2004). Today, droughts in industrialized countries practicing intensive agriculture can lead to accentuated effects in the global agriculture economy.

The Corn Belt of the U.S. is particularly vulnerable to economic losses due to drought. At the heart of this region, Iowa is one of the top five states in terms of agricultural production, accounting for 6.9% of the national value of agricultural products sold (USDA, 2009). Iowa and Missouri combined produce nearly $28 billion annually in agricultural products (USDA, 2009). Recent severe droughts affecting the Corn Belt include the droughts of 1988 and 2006–7, which amounted to over $40 billion and $11 billion in losses, respectively (Ross and Lott, 2003; NCDC http://lwf.ncdc.noaa.gov/oa/reports/billionz.html#chron). The economic impact of

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a decade-long drought in the Corn Belt region would be staggering to say the least.

Faced with the realities of increasing economic losses due to drought, drought mitigation has become an important priority for many U.S. states. Mitigating the impacts of drought through planning and preparedness has the potential to save billions of dollars. One aspect of drought mitigation involves increasing our ability to predict the onset and duration of drought events. Empirically based drought projections aid in mitigating drought effects, but currently their predictive ability is very limited and unreliable for temperate regions such as the Corn Belt. Improvement in drought prediction relies in part on construction and validation of climate models using paleoclimate proxy data (Seager et al., 2008). Natural archival records (e.g., tree rings, ice cores, lake sediments, speleothems, corals) provide our best paleoclimate resources for understanding the historic range of drought variability. Tree rings are a unique paleoclimate proxy in that they are precisely dated, their widths can be highly correlated and calibrated to drought, and they have the potential to provide annual to sub-annual drought information. Current tree-ring records in the Midwestern U.S. are limited to about the last 400 years. Longer records of drought and climate variability are needed in this critical region – the breadbasket of the United States.

The objectives of this research were to (1) develop a reconstruction of drought from a recently constructed long oak (*Quercus macrocarpa, Q. bicolor*) tree-ring chronology (AD 912–2004; Stambaugh and Guyette, 2009) and, from this reconstruction, (2) characterize the historic occurrence, duration, and frequency of drought events. We hypothesized that our tree ring climate response function analysis would indicate similar driving climatic factors as other tree-ring studies in the region. We hypothesized that multidecadal droughts occurred during the last millennium and that known periods of prolonged drought (e.g., Medieval Warm Period [Lamb, 1965], sixteenth-century megadrought [Stahle et al., 2000]) are reflected in our drought reconstruction. Lastly, we hypothesized that the bidecadal drought rhythm, shown to persist in the Corn Belt back to the mid-16th century (Meko et al., 1985), was a persistent feature through the last millennium.

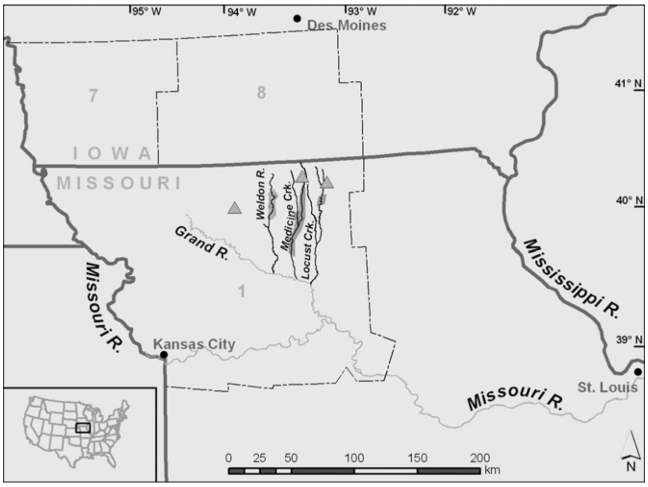

Fig. 1. Locations of the study streams in the upper Grand River watershed. The tree-ring chronology was developed from logs recovered from tributary streams (grey sections) and cores from live trees (triangles). Polygons (dash-dot border) represent state climate divisions from which instrumental drought data were summarized and used for calibration and verification of the tree-ring chronology.

2. Methods

2.1. Climate data

Climate data consisted of monthly time-bias-corrected divisional data of temperature, precipitation, and both Palmer Drought Severity Index (PDSI) and Palmer Hydrologic Drought Index (PHDI) (Palmer, 1965). The primary difference in the two drought indices is that PDSI is a meteorological index related to droughts associated with weather while PHDI is a hydrological index used to assess long-term moisture supply. All data are compiled by the National Climate Data Center and available through the National Oceanic and Atmospheric Administration (NOAA) online archive (NCDC, 1994). Data spanning years 1895–2004 were obtained for climate divisions in Iowa (Divisions 7, 8) and Missouri (Division 1) that encompass the region from which tree-ring samples were collected (Fig. 1). Previous dendroclimatological studies have emphasized the benefits of using divisional over single station data (Blasing et al., 1981).

2.2. Tree-ring data

Tree-ring data were derived from a master oak ring-width chronology spanning the period AD 912 to 2004 (Fig. 2). The chronology was developed from live tree cores and sections of subfossil trees collected from the region of northern Missouri and southern Iowa, USA (Fig. 1) (Guyette et al., 2008; Stambaugh and Guyette, 2009). Ring-width time series of individual trees contain variability due to influences other than climate (Fritts, 1976). In order to reduce the component of ring-width variability not related to climate, individual tree-ring series were detrended prior to developing standardized ring-width chronologies (Cook, 1985). Two methods of detrending were compared with respect to drought reconstruction. The purpose of the first method was to

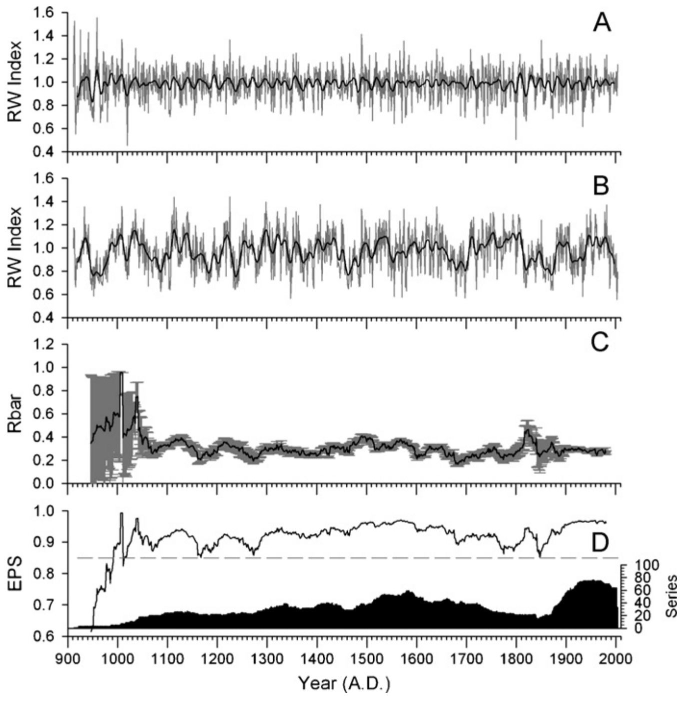

Fig. 2. Time plots of tree-ring chronologies and common-signal-strength statistics. (A) High frequency (Hfreq) ring-width index chronology (grey) with 15-yr weighted moving average (black). (B) Low frequency (Lfreq) ring-width chronology (grey) with 15-yr weighted moving average (black). (C) Running Rbar (Wigley et al., 1984) calculated on 50-yr segments with 1-yr time step. Grey bars are one standard error. (D) Expressed population signal (EPS) calculated on 50-yr segments with 1-yr time step. Dashed line indicates the 0.85 threshold used for judging chronology signal fidelity. Black bars indicate the total number of series represented in each year of the chronology.

develop a ring-width chronology containing only high frequency variations in climate. For this high frequency chronology (Hfreq), ring-width series were detrended twice – first with a negative-exponential curve or linear regression line to remove linear and non-linear growth trends and then with a 32-year spline curve to reduce low-frequency variation in ring-widths induced by exogenous (e.g., fire, wind) and endogenous (e.g., competition, tree-site characteristics) growth influences (Cook and Peters, 1981). The purpose of the second detrending method was to develop a ring-width chronology that preserved the lowest frequency variations possible. For this low frequency chronology (Lfreq), ring-width series were detrended using stiff spline curves (for live trees) and regional curve standardization approach (RCS) (Briffa et al., 1992; Esper et al., 2003) for subfossil wood. The RCS method utilizes a pith-aligned mean growth curve derived from all series to remove biological trends. Detrending was by the ratio method (Cook, 1985), such that the Lfreq and Hfreq detrended series are stationary with a mean of 1.0. All subsequent analysis used standardized ring-width chronologies whereby indices from individual samples were averaged into site chronologies using a robust bi-weight mean (Cook, 1985). Chronology variance was stabilized using the Rbar-weighted method which adjusts time-dependent variance utilizing sample size and between-series correlation (Osborn et al., 1997). Common variance in the chronology (signal) was measured using the expressed population signal (EPS) statistic (Briffa and Jones, 1990; Wigley et al., 1984). EPS was evaluated using 50 yr segments on a 1 yr step (Fig. 2). As suggested (Wigley et al., 1984) and employed in similar studies (Pederson et al., 2004; St. George and Nielsen, 2002; Woodhouse, 2003), the chronologies were truncated when the EPS fell below 0.85 (i.e., a general guide for when the amount of noise in a chronology becomes unacceptable). Truncation resulted in a trimming of the useable portion of data for reconstruction to the period AD 992–2004.

2.3. Ring-width climate response

Pearson correlations were calculated between the Hfreq chronology annual ring-width indices and monthly climate variables (i.e., temperature, precipitation). From these results and previous findings using comparable materials and methods (Cleaveland and Duvick, 1992) we chose to relate ring-widths to climate using a drought index that integrates the growing season temperature and precipitation signal. We considered as candidates the PHDI and the closely related PDSI, and chose the PHDI for two reasons – the trees are primarily from riparian settings, and chronologies were found to correlate generally higher with PHDI than with PDSI. Biologically, riparian oak tree growth is plausibly better represented by the PHDI because relatively deep root penetration and the riparian setting would favor dependence on deep and time-lagged water supplies. In addition, summer season (JJA) PHDI was chosen because: (1) summer is most biologically relevant (corresponds to growing season) and summer PHDI exhibits highest correlation with both temperature and precipitation, (2) summer PHDI has been previously shown to adequately represent the integrated climate response of trees in the region (Cleaveland and Duvick, 1992), (3) a reconstruction of the summer period would be temporally aligned with and comparable to other regional drought reconstructions (e.g., North American Drought Atlas (Cook et al., 2004)), and (4) present day row-cropping agriculture, the dominant land use of broad riparian floodplains, is highly dependent on climate conditions in summer.

The predictive ability of the Hfreq and Lfreq chronologies was tested separately on a reduced period of record spanning years 1931–2004. This period was chosen because prior to 1931 limited climate station data existed for characterizing divisional climate

Table 1
Ranges of Palmer Hydrologic Drought Index (PHDI) for various drought classes. Adjusted ranges for reconstructions yield same total frequency (number of years) in a given class by either observed or reconstructed data for the model calibration period (see Section 2).

Observed	Class	Hfreq recon.	Lfreq recon.
$x \le -4.0$	Extreme drought	$x \le -3.19$	$x \le -2.30$
$-4 < x \le -3$	Severe drought	$-3.19 < x \le -1.82$	$-2.30 < x \le -1.61$
$-3.0 < x \le -1.50$	Mild/moderate drought	$-1.82 < x \le -0.80$	$-1.61 < x \le -0.43$
$-1.50 < x < 1.50$	Near normal	$-0.80 < x < 0.71$	$-0.43 < x < 0.68$
$1.50 \le x < 3.0$	Mild/moderate wetness	$0.71 \le x < 3.01$	$0.68 \le x < 2.77$
$3.0 \le x < 4.0$	Severe wetness	$3.01 \le x < 3.84$	$2.77 \le x < 3.05$
$x \ge 4.0$	Extreme wetness	$x \ge 3.84$	$x \ge 3.05$

(NCDC, 1994). Calibration of the ring-width index to mean summer season PHDI began by using the split-sample verification technique (Meko and Graybill, 1995) whereby regression analysis was used to calibrate the tree-ring index on one half of the period (1931–1967) and verified on the other half (1968–2004). The process was repeated by switching the calibration and verification periods. After judging that split-sample models were consistent and statistically robust, a final transfer function was developed using stepwise multiple linear regression that related the ring-widths to PHDI for the post-1930 period. Three backward-lagged predictors were considered as potential predictors in the regression analysis to account for lagged and autocorrelated growth effects. Regression analysis resulted in separate models predicting PHDI from the Hfreq and Lfreq ring-width chronologies. The rationale for having two different reconstructions was that the Hfreq reconstruction has better skill for characterizing single-year and short-term droughts, while the Lfreq reconstruction is expected to better characterize lower frequency variation and longer duration droughts. The predictive ability of both resulting reconstructions was assessed using the sign test, product means test, and the reduction of error (RE) test (Fritts, 1976). In addition, a contingency analysis was conducted to examine how well drought conditions were predicted in a categorical classification. Because regression necessarily leads to compression of predictand variance, it was necessary to relax the thresholds for various PHDI classes (e.g., extreme drought) on reconstructed PHDI before forming contingency tables (Table 1). Thresholds for the reconstructions were adjusted from the empirical cumulative distribution functions of observed and reconstructed PHDI. The threshold for reconstructed PHDI was adjusted such that the total number of cases falling in a given PHDI class for the common period (calibration period) was the same for reconstructed and observed PHDI.

2.4. Drought severity, duration and frequency

Drought severity was defined based on the Hfreq reconstruction since it demonstrated greater reconstructive skill over the instrumental period. Drought durations (number of years) were described based on the Lfreq reconstruction because it preserves low frequency variability. Drought durations represented the number of years in which PHDI values remained negative using a 15-yr moving average of the low frequency drought reconstruction.

It is well documented that quasi-periodic variation reflecting irregular drought cycles is detectable in tree-ring time series (Stockton and Meko, 1983; Cook et al., 1997; McCabe et al., 2004). Spectral properties of the drought reconstructions were analyzed by the smoothed periodogram method (Bloomfield, 1976) for the purpose of identifying periodicities or quasi-periodicities in drought. Preliminary steps in analysis of the reconstructed drought indices from the Hfreq and Lfreq chronologies included: subtraction of the sample mean, tapering 5% of each end of the series, and padding to a length of 1024 years by appending zeros. Series were then transformed into raw periodograms using the discrete Fourier transform with a fast-Fourier-transform algorithm. The raw periodograms were smoothed into estimates of sample spectra by smoothing successively with Daniell filters of spans 7 and 11, and 95% confidence intervals for spectra were computed using a chi-square distribution (Bloomfield, 1976). Spectral peaks were tested for statistical significance against an empirical null continuum (Meko et al., 1985), which for our series was generated by smoothing raw periodograms successively with Daniell filters of length 143 and 201. Peaks in the spectra were considered significant at 95% if the lower confidence interval did not include the null continuum.

3. Results

Climate response analysis confirmed that oak growth is negatively correlated with temperature and positively correlated with precipitation, notably during summer months (Fig. 3). Proceeding with an integrated temperature-precipitation response via drought indices, we found PHDI to be better predicted than PDSI with highest and significant ($p < 0.01$) correlations between PHDI and ring-width for the summer season (June to August) (Table 2). The highest explanatory power was attained with a mean PHDI value generated from the three surrounding climate divisions as opposed to single climate station or divisional data. The split-sample calibration and verification process showed ring-widths were more highly correlated to PHDI during the period prior to 1968 than after.

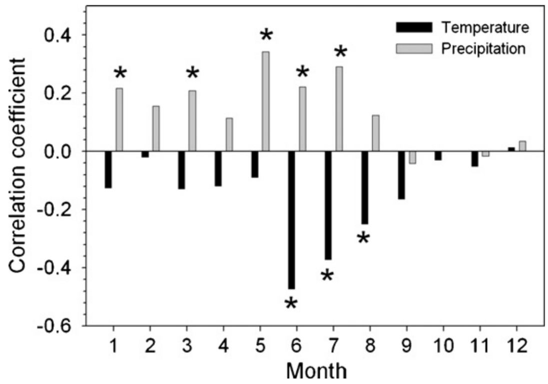

Fig. 3. Correlation coefficients for monthly temperature and precipitation against the high frequency tree-ring chronology. Stars indicate significant monthly variables at 95% significance. Based on the integrated temperature and precipitation signal during primarily summer season months we chose to develop the reconstruction using summer season drought indices.

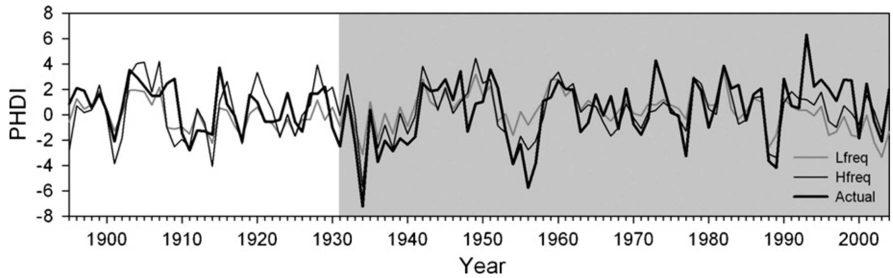

Fig. 4. Time series of actual (bold black line) and reconstructed (thin grey and black lines) summer season (JJA) Palmer Hydrologic Drought Index (PHDI), 1895–2004 for the region of northwest Missouri and southwest Iowa. The calibration period is shown with grey background.

Table 2
Calibration and verification statistics for a summer season (June–August) Palmer Hydrologic Drought Index (PHDI) reconstruction using both a high and low frequency tree-ring chronology. (A) Regression results between instrumental PHDI and ring-width using a split-sample technique. (B) Final reconstruction model details (based on the 1931–2004 calibration) (grey shade). (C) Verification results based reconstructed summer PHDI for the full instrumental period (1895–2004).

High frequency (Hfreq)
(A) Regression results

Calib. period	n	R^2	Adj R^2	SE[a]
1931–1967	37	0.65*	0.63*	1.63
1968–2004	37	0.54*	0.42*	1.61
1931–2004	74	0.57*	0.56*	1.68

Low frequency (Lfreq)
(A) Regression results

Calib. period	n	R^2	Adj R^2	SE[a]
1931–1967	37	0.66*	0.64*	1.61
1968–2004	37	0.34*	0.30*	1.94
1931–2004	74	0.32*	0.31*	2.11

High frequency (Hfreq)
(B) Regression coefficients (1931–2004)

Predictor	B	SE of B	p[b] level
Intercept	−19.171	2.247	<.0001
RW	14.733	1.618	<.0001
RW-1	4.985	1.627	0.0031

Low frequency (Lfreq)
(B) Regression coefficients (1931–2004)

Predictor	B	SE of B	p[a] level
Intercept	−7.996	1.424	<.0001
RW	8.363	1.415	<.0001

High frequency (Hfreq)
(C) Verification results (1895–2004)

Sign test (agree/disagree)	r	PM[c] test	RE[d]
(81/28)	0.68	4.14*	0.41

Low frequency (Lfreq)
(C) Verification results

Sign test (agree/disagree)	r	PM[c] test	RE[d]
(79/30)	0.57	3.45*	0.32

[a] The standard error of estimated June–August PHDI.
[b] p level is the statistical significance of the independent variable's t value.
[c] A significant value for the product means (PM) test indicates that both the signs and the magnitudes of estimated and observed June–August PHDI exhibit a real relationship (Fritts, 1976).
[d] A positive reduction of error (RE) value demonstrates that the regression model is a better estimator of summer PHDI than the mean of the calibration period (Fritts, 1976).
* Significant at the $p = 0.01$ level. SE = standard error; RW = ringwidth chronology.

Table 3
Contingency analysis for both the high and low frequency drought reconstructions. Observed and reconstructed PHDI were ranked and sorted according to seven drought categories (Palmer, 1965). For example, 2 of the 5 extreme drought years in the Hfreq reconstruction were also extreme drought years in the observed record, 1 was severe drought, 2 were mild/moderate drought, and none of the years were near normal or wetter.

Reconstructed PHDI	Observed PHDI						
	Extreme drought (≤−4.0)	Severe drought (−3.99 to −3.00)	Mild/moderate drought (−2.99 to −1.50)	Near normal (−1.49 to 1.49)	Mild/moderate wetness (1.50 to 2.99)	Severe wetness (3.0 to 3.99)	Extreme wetness (≥4.0)
Hfreq							
Extreme drought	2/5	1/5	2/5	0/5	0/5	0/5	0/5
Severe drought	1/11	3/11	3/11	3/11	1/11	0/11	0/11
Mild/moderate drought	0/14	1/14	5/14	6/14	2/14	0/14	0/14
Near normal	0/34	0/34	5/34	20/34	8/34	0/34	1/34
Mild/moderate wetness	0/35	0/35	0/35	9/35	22/35	3/35	1/35
Severe wetness	0/5	0/5	0/5	2/5	2/5	1/5	0/5
Extreme wetness	0/6	0/6	0/6	2/6	3/6	1/6	0/6
Lfreq							
Extreme drought	1/3	1/3	1/3	0/3	0/3	0/3	0/3
Severe drought	0/9	2/9	3/9	2/9	2/9	0/9	0/9
Mild/moderate drought	2/22	0/22	6/22	9/22	5/22	0/22	0/22
Near normal	0/37	2/37	4/37	17/37	12/37	1/37	1/37
Mild/moderate wetness	0/34	0/34	1/34	12/34	17/34	3/34	1/34
Severe wetness	0/3	0/3	0/3	1/3	2/3	0/3	0/3
Extreme wetness	0/2	0/2	0/2	1/2	2/2	0/2	0/2

The full period regression model utilizing the Hfreq chronology explained 56% of the variance (adjusted R^2) in PHDI while the full period regression model utilizing the Lfreq chronology explained 31% of the variance (Table 2 and Fig. 4). Regression modeling indicated a contemporaneous (no lags) dependence of PHDI on the Lfreq chronology and a distributed–lag dependence (t and $t-1$) of PHDI on the Hfreq chronology. Verification tests revealed that both regression models exhibited significant reconstructive skill (Tables 2 and 3) and were suitable to hindcast PHDI back to AD 992.

For the instrumental period, dry modes were more closely predicted than wet (Table 3). Prediction error was greatest during extremely wet years (e.g., 1972, 1993), which are sometimes characterized as having normal moisture conditions by the ring-widths. Individual drought years and periods of prolonged drought were tracked by the Hfreq reconstruction.

3.1. Reconstructed Palmer Hydrologic Drought Index, AD 992–2004

The Hfreq and Lfreq reconstructions of PHDI (Fig. 5) visually exhibited two important features: (1) considerable variability on decadal (Hfreq)-to-century (Lfreq) timescales, and (2) pre-instrumental drought conditions unlike those of the modern period (since 1895). The instrumental record appeared to not be representative of the full range of variability, severity, or duration of drought during the last millennium. The Hfreq reconstruction exhibited a significant spectral peak near the 0.05 frequency yr^{-1} (20 yr period) – a feature that was visually apparent and persistent in the time series plot. The spectral peak near 20 years likely resulted at least partly from the data processing: variance removal at wavelengths longer than 20 years by the 32-year spline used in detrending ring widths to produce the Hfreq chronology. A series

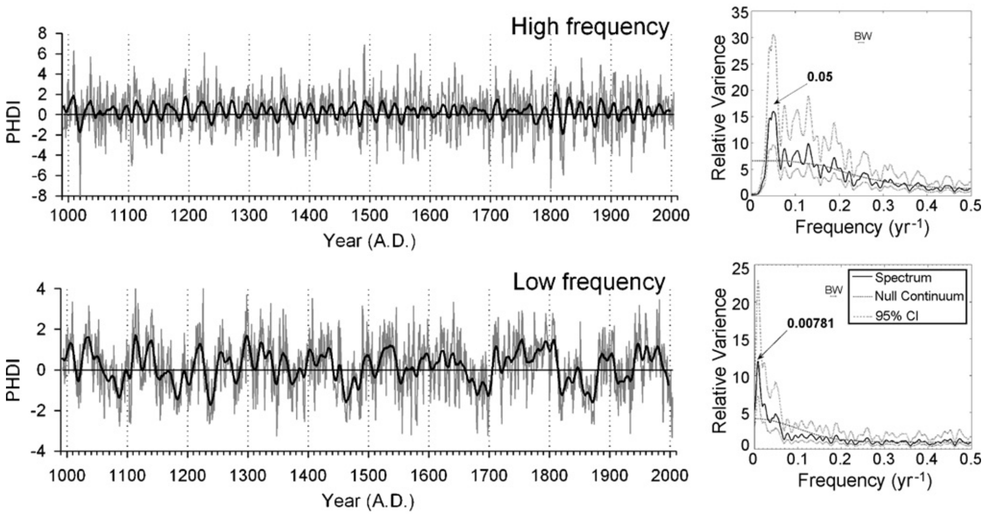

Fig. 5. High and low frequency reconstructions of Palmer Hydrologic Drought Index (PHDI) for the period 993–2004. Annual reconstructed PHDI (grey) and a 15-yr weighted moving average are shown for both methods. Spectra of reconstructed annual PHDI with significant peaks indicated where the lower 95% confidence interval exceeds the null continuum.

Table 4
Driest years and decadal (≥10 yrs) droughts during the last millennium (AD 993–2004) as reconstructed from tree-ring widths.

Driest years			Decadal/multidecadal droughts			
Rank	Year	PHDI[a]	Period	Duration (yrs)[b]	Min. value[a]	Severity rank
1	1020	−8.42	1148–1208	61	−3.84	9
2	1800[c]	−7.24	1661–1705	45	−4.87	4
3	1821	−5.95	1060–1097	38	−3.89	7
4	1934[c]	−5.68	1455–1489	35	−3.89	7
5	1736	−5.30	1849–1880	32	−4.88	3
6	1820	−5.17	1909–1938	30	−5.68	2
7	1106	−5.05	1815–1844	30	−5.95	1
8	1874[c]	−4.88	1229–1248	20	−2.98	10
9	1698	−4.87	1368–1384	17	−4.28	6
10	1556	−4.84	1548–1560	13	−4.84	5

[a] Based on Hfreq reconstruction.
[b] Duration based on 15-year weight Lfreq reconstruction.
[c] Correspond to Iowa's 15 driest years from AD 1640–1982 (Cleaveland and Duvick, 1992).

generated by a simple autoregressive process and detrended by such a spline will have a spectral peak somewhere in the frequency range over which the response function of the spline is non-zero. That the much more conservatively detrended Lfreq PDHI reconstruction also had a minor peak near 20 years is perhaps stronger support for a bi-decadal drought rhythm. The Lfreq reconstruction had its major spectral peak near the 0.00781 frequency yr^{-1} (128 yr period) (Fig. 5). This peak may represent a century-scale rhythm in drought, but to some extent may also be due to the spectral alteration associated with ring-width detrending.

Characterization of the most severe historic drought years was done using both the Hfreq and Lfreq reconstructions. Of the ten driest years, four were common between both reconstructions (Table 4). Years AD 1020 and 1348 were the driest for the Hfreq and Lfreq reconstructions, respectively. The year 1934 was the driest during the instrumental period and was among the top five driest years in the last millennium according to both reconstructions. According to the Lfreq reconstruction, three of the top ten most severe droughts occurred within a 25 year period corresponding to the late 16th century.

Thirteen decadal to multidecadal droughts (i.e., ≥10 years) occurred during the last millennium based on the 15-yr weighted mean of the Lfreq reconstruction. Of these decadal to multidecadal droughts, the longest occurred in the latter half of the 12th century and lasted approximately 61 years (AD 1148–1208) (Table 4). For comparison, the well-documented 20th century Dust Bowl drought lasted about half as long (30 years) using this method and ranked 6th and 9th in the last millennium in terms of duration and severity, respectively. The four longest droughts occurred prior to EuroAmerican settlement of the region (ca. AD 1850). For individual centuries, both the 12th and 19th centuries had equal numbers of dry years ($n = 62$); however, PHDI values were lower (more severe) on average during the 19th century.

4. Discussion

4.1. Tree-ring climate response

We questioned whether the climate signal in our chronologies would match that of other chronologies from the region because the riparian setting of our samples contrasted with the typical upland setting of existing chronologies. The full-period regression model (Hfreq reconstruction) explained up to 56% of the variance of summer PHDI. This compares favorably with the explanatory power of similar reconstructions in the region (Stockton and Meko, 1983; Cleaveland and Duvick, 1992; see Table 4 in Woodhouse and Overpeck, 1998). Long oak tree-ring chronologies such as ours are typically constructed from trees growing in or near wet environments, as water is the cause for burial and preservation. In these environments ring-widths may be better predictors of dry conditions than wet because of the negative growth effects incurred during periods of extreme wetness (e.g., reduced soil aeration, accumulation of toxic compounds, and changes in physical soil properties). The effect can lead to overall decreases in strength of the common-growth signal within the populations of trees because the extreme wetness may vary over the site and not be limiting to growth of all trees. Despite this potential problem, the chronology signal strength as measured by the EPS remained high during the full period (AD 992–2004). Contingency analysis showed that extreme wetness was less accurately predicted than extreme dryness. The somewhat higher split-sample correlations for 1931–1967 than for 1968–2004 may be due at least partly to relative abundance of dry years in the earlier period. It is possible, however, that other factors may have been important (e.g., increases in available nutrients (P, N) from industrial agricultural practices). Decrease in the EPS in the interval 1830–1860 coincides with a decrease in the number of tree-ring series in the record. The decrease in available series is likely attributable to influences of regional land settlement – a feature evident in chronologies from other regions (St. George and Nielsen, 2002).

Likely one of the greatest concerns with the drought reconstruction is whether or not low frequency variability in drought was preserved through our detrending methods. In tree-ring series, difficulty arises in preserving low frequency information longer than the tree life span (Cook et al., 1995). Accurate characterization of drought conditions is highly dependent on the ability to retain low-frequency signals and overcome any single proxy or site biases. We suggest that low frequency variability in the drought reconstructions was maintained based on Hfreq reconstructed decadal drought periods corresponding with (1) decadal droughts documented in the Great Plains and central Mississippi Valley regions (Cook et al., 2007), (2) prolonged drought episodes reconstructed from lake sediments in North Dakota (Laird et al., 1996), and (3) some extended periods of low flow for the White River (Cleaveland, 2000).

4.2. Comparisons between instrumental and reconstructed drought

Reconstructed drought tracks instrumental drought well at interannual to decadal time scales (Fig. 4). Prolonged 20th century severe droughts (e.g., 1930s, mid-1950s) and short-term moderately severe droughts (1900–01, 1988–89) are clearly represented in the tree-ring reconstruction. Interannual variability in the instrumental record during the Dust Bowl period (1929–1940) was reproduced by both the Hfreq and Lfreq reconstructions. The 1950s drought is also depicted, though the reconstructed severity was less than indicated in the instrumental record. From the aforementioned problems associated with reconstructing extremely wet years, it is not surprising that the extremely wet years (1973, 1993) with PHDIs > 4.0 were poorly predicted (Fig. 4). Despite these errors, wet periods (3–10 yrs) may still be adequately portrayed. For example, wet periods during the early 20th century (1902–1907, 1943–1951) were represented in the reconstruction.

4.3. Comparisons to climate proxies

4.3.1. AD 1500–2004

The drought reconstruction presented here suggests that 20th century droughts, including the Dust Bowl, were relatively unremarkable when compared to drought durations prior to the instrumental record. Though the Dust Bowl was not the longest drought it was severe compared to other decadal and longer droughts of the last millennium (Table 4). Noting the similarities to climate reconstructions of neighboring regions aids in depicting the drought footprint and confirming both the occurrence and severity of past droughts. Each of the five decadal droughts identified for the period AD 1500–2004 (see Table 4) coincides with a multi-year drought identified by at least one other regional study. The best match is with the reconstruction of Iowa July PHDI (Cleaveland and Duvick, 1992): four of the six driest decades correspond to decadal droughts in our reconstruction. Three of our driest years (1800, 1874 and 1934; Table 4) match the driest years identified in Iowa and also match historic droughts in western Nebraska (Weakly, 1943).

Recently, studies have increasingly depicted central U.S. drought during the 19th century as unique (Woodhouse and Overpeck, 1998; Woodhouse et al., 2002; Cook et al., 2004; Herweijer et al., 2006). Several lines of evidence (e.g. active dune sands, tree rings, instrumental records, written accounts) indicate that the 19th century was marked by several periods of extended drought in the Great Plains region (Woodhouse and Overpeck, 1998). This is also evident in our reconstruction: the 19th century had four of the top ten driest years (Hfreq reconstruction), and a total of 62 years with negative PHDI values (Lfreq reconstruction). Both the Lfreq and Hfreq reconstructions characterize the 19th century as the driest of the last millennium. With the Lfreq reconstruction, the number of dry years in the 19th century was equal to those of the 12th, century, although the 19th century had a lower average PHDI. Major drought periods of the 19th century occurred from about 1816 to 1844 and 1849 to 1880. This period corresponds to the transition out of the Little Ice Age when cooler temperatures from reduced radiative forcing characterized the northern hemisphere (Jones et al., 2001; Crowley, 2000), and in particular, the northern Great Plains (Laird et al., 1996). During the 1816–1844 period, prolonged droughts were also reported in Arkansas (1830–1840; Stahle et al., 1985) and Nebraska (1822–32; Weakly, 1943). Drought was particularly widespread and severe around 1820 as documented by paleoclimatic records throughout the central U.S. (Woodhouse and Brown, 2001; Cleaveland and Duvick, 1992; Meko, 1992). During this period, independent written accounts reported eolian activity in central Kansas (Muhs and Holliday, 1995) while diatoms in lake sediments suggest abrupt transition to colder temperatures in North Dakota (Laird et al., 1996).

The latter 19th-century drought mode (i.e., 1849–1880) coincides with a severe persistent drought that included the western Great Plains (Woodhouse et al., 2002). Within this dry mode, widespread and severe drought centered on the Great Plains region corresponded to the Civil War era (1855–1865; Herweijer et al., 2006; Fye et al., 2003). The Civil War drought was significant in that it rivals the Dust Bowl drought as potentially the longest drought since AD 1500 in the central U.S. (Fye et al., 2003).

The Lfreq reconstruction indicates much of the 18th century was wetter than normal. That reconstruction is consistent with Cleaveland and Duvick (1992) in identifying 1771–1773 as the driest period of the 18th century, and classifying 1721 and 1736 as the only other two extreme drought years of the century. Conversely, the latter 17th century was a period of prolonged drought (ca. 45 yrs; Table 4) exceeded by only one other drought in the last millennium. This multidecadal drought corresponds to the Maunder Minimum – a period of decreased radiative forcing (Crowley, 2000) and increased volcanic eruptions. The occurrence of extreme and prolonged drought in the central U.S. during the 17th century is supported by the North American Drought Atlas (Cook et al., 2007). An approximately 92-yr gap in the Moon Lake, North Dakota, salinity record (Laird et al., 1996) occurs during this period due to desiccation and further suggests a multidecadal drought, or megadrought. Perhaps the best documented megadrought in the last 500 years is the 16th century megadrought, which affected much of North America and caused population collapse throughout the southwestern U.S. and Mexico (Stahle et al., 2000; Acuña-Soto et al., 2002). Presence of a prolonged 16th century megadrought in our record is somewhat inconclusive. A decadal drought occurred during the mid-16th century (1548–1560), but at an earlier date than what other studies have defined as the 16th century megadrought period (Stahle et al., 2007; Stockton and Jacoby, 1976; Meko et al., 1995; Fritts, 1965). The somewhat earlier drought period may have been restricted to a more limited area, such as Missouri and Arkansas. Some support is offered by Stahle et al. (1985), who identified 1549–1577 as likely the worst drought in Arkansas in the past 450 years. The larger and longer-duration 16th-century megadrought likely had a varied spatio-temporal "footprint" which at times affected the central U.S. Two years during the megadrought (1571 and 1580) were exceptional and ranked in the top ten driest years at our site during the last millennium. Interestingly, more buried trees have dated to the 16th-century megadrought period than any other period in the last millennium.[1]

4.3.2. AD 992–1500

Descriptions of central and eastern U.S. droughts prior to AD 1500 are lacking because very few annually resolved proxies span this period. Our chronology exhibits a significant climate signal throughout this period, highlighted by three of the four longest droughts of the last millennium. An approximately 35-yr drought in the mid- to late-15th century coincides with a reconstructed drought for northern New Mexico (Grissino-Mayer, 1996). Like the droughts we document for the early-19th and mid-17th centuries, the 15th-century drought corresponds to a period of decreased radiative forcing and northern hemisphere temperatures (Crowley, 2000; Mann et al., 1999).

In the thirteenth-century the most severe multidecadal drought in the entire record occurred during the 20-yr period 1229–1248 (Table 4). This drought pre-dates by several decades the end-of-century "Great Drought" of the Pueblo area in the Southwest (Douglass, 1935). A drought almost twice as long occurred in the late 11th century (Table 4), but the approximately 61-yr drought in the late 12th century (ca. AD 1148–1208) appears to be the most significant drought of the entire reconstruction. This period corresponds to the single greatest megadrought in North America during the last 2000 years (Cook et al., 2007) and unmatched persistent low flows in western U.S. river basins (Meko et al., 2007). The region affected by this drought appears to have also included portions of the central U.S (Laird et al., 1996). This drought marks the middle of the Medieval Warm Period – an interval of warmer

[1] The larger number of trees in the sample population during the 20th century (Fig. 2) is due to contributions from cores taken from live trees.

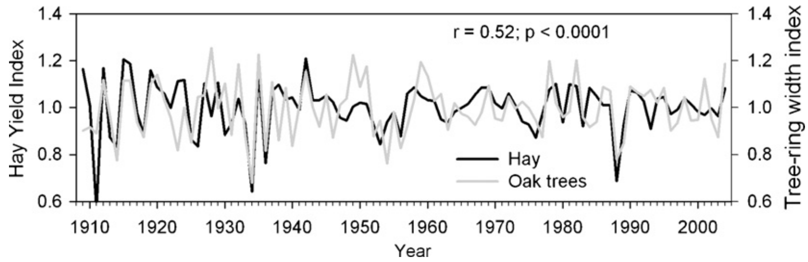

Fig. 6. Annual changes in hay yield and tree growth from 1909 to 2004. Hay yield is an index of mean annual state yields for Missouri and Iowa (data source: National Agricultural Statistics Service). The hay index represents detrended and standardized values (mean = 1.0). Tree-ring index is the Hfreq tree-ring chronology.

temperatures between approximately AD 800–1300 characterized by greater drought duration and frequency in the Northern Great Plains compared to more modern times. Our drought reconstruction confirms this megadrought extended also to the agricultural region of the central U.S. The drought likely added to the apparent cultural and political unrest reported in the Cahokia culture (Benson et al., 2007), whose geographic center was located approximately 300 km to the east of our study area. Even though the late-12th century megadrought seems extraordinary, even longer centennial-scale droughts have occurred in the mid-continental U.S. during the Holocene (Booth et al., 2005).

4.4. Periodicity in the reconstruction

Drought episodes have been attributed to many factors ranging from small-scale land use practices to solar variability. From previous studies of drought in the Corn Belt, a quasi-bidecadal drought rhythm was shown to persist in the Corn Belt back to the late-17th century (Meko et al., 1985). Our findings – a major spectral peak near 20 yr in the Hfreq reconstruction and minor spectral peak near 20 yr in the Lfreq reconstruction – suggest a bidecadal rhythm in drought is a persistent feature of the past millennium. The Hfreq spectral peak is somewhat problematic because of filtering effects of tree-ring standardization, but the Lfreq spectral peak should be well outside the range of such effects. The periodicity was previously hypothesized as a manifestation of the lunar nodal and Hale magnetic solar cycles. Though a physical mechanism linking the bidecadal cycle to climate is still lacking, the cycle recurs as an important component of decadal climate variability in the central U.S. manifested through regional variations in tree growth (Meko et al., 1985; Stambaugh and Guyette, 2004), changes in drought area of the western U.S. (Cook et al., 1997), instrumental precipitation (Currie and O'Brien, 1990), and lake salinity records (Laird et al., 1996).

A sub-decadal frequency component (at a period of approximately 7.8 years) is often detected in tree-ring reconstructions of drought over the central United States and has been linked to a leading effect by the North Atlantic Oscillation (Fye et al., 2006). Based on our spectral analysis, a peak in variance power at a 7.7 yr period was present and marginally significant in the Hfreq reconstruction (Fig. 5). Closer inspection of this frequency mode is needed with respect to coherency with other tree-ring chronologies, associations with NAO proxies, and temporal changes in power. Through work such as this, the importance of constructing and lengthening this annually resolved tree-ring chronology is revealed as this reconstruction may provide the only information available concerning changes and strength of the NAO over the Midwest during the past millennium.

The length of the oak drought reconstruction is perhaps its greatest strength in contributing to the understanding of climate cycles or quasi-periodicities. Added temporal depth aids in understanding the persistence of drought rhythms and in identifying longer modes of variability. The major spectral peak near 128 yr in the Lfreq reconstruction is a topic for future study. The extent to which this peak reflects standardization operations or segment-length limitations requires more attention. At this time little is known about the plausible mechanisms for a 128 yr cycle in drought.

4.5. Implications for agriculture

Perhaps one of the most important applications of these results is towards understanding the implications of drought for agricultural production. Our long drought record provides a much longer temporal perspective on the potential growing season conditions of the Corn Belt including drought durations previously unrepresented in the tree-ring record. Future research investigating how drought relates to agricultural production would likely be very beneficial. For example, how do annual drought indices or tree-ring widths translate to agricultural yields for different crops?

Although the region of northern Missouri and Iowa has been a highly productive region during the last few decades, the duration and severity of historic droughts suggests that potential exists for much lowered productivity. Despite their utility for reconstructing past climate conditions, tree ring-widths are foremost a metric of annual biological growth. Regional crossdating, or pattern matching, of absolutely dated ring-width series and anatomical wood features through time attests to the climate control on annual growth. Intriguingly, preliminary work suggests that our long tree-ring chronology is significantly correlated to regional hay yield (Fig. 6) – a relationship we assume is related to similarities in climate-growth response. Hay yield and tree growth both decrease during increased drought and may also decrease when conditions are extremely wet. At annual time-scales the tree-crop growth parallel is perhaps most apt for those crops whose growth and yields integrate climate over much of the growing season. Hay appears to be a crop of this type because (1) its growth occurs over a long period, and (2) yields are based on total above-ground biomass and are not dependent upon flowering success. Conversely, we expect grain crops are less related to tree-growth at annual time scales because yield metrics often depend on specific growing season conditions such as during the periods of flowering, seed set, and seed development (Chang, 1968). Experiments to quantify possible relationships between tree growth, various agricultural yields, and climate could provide much-needed answers for both the scientific and agricultural communities however have not yet been done.

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