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PROGRESS IN CONSTRUCTING A LONG OAK CHRONOLOGY FROM THE CENTRAL UNITED STATES

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ABSTRACT

We describe methods and progress in developing the American Long Oak Chronology (ALOC), an effort to construct an oak tree-ring chronology from the Central US that spans the Holocene. Since 2000, we have collected and measured ring widths on over 550 pieces of subfossil oak (*Quercus*) wood. Over 330 oak samples have been radiocarbon dated, with ages ranging up to 14,000 cal yr B.P. A 1,093-year-long tree-ring record has been constructed from live and subfossil bur oaks (*Q. macrocarpa* Michx.) and swamp white oaks (*Q. bicolor* Willd.) growing along and buried in sediments of streams that flow through northern Missouri and southern Iowa, USA. Here we describe the ALOC for the period A.D. 912–2004 to demonstrate its dendrochronological value, display the material quality, and emphasize the importance of chronology construction. We also report on progress in developing older floating chronologies. The development of more long, multi-millennium chronologies will be an important contribution to dendroclimatology. These chronologies will be particularly useful to the Central US, a region with a continental climate and limited temporal depth of annually resolved paleo-records. Perhaps more critical is its location in the middle of one of the most important agricultural regions in the world.

Keywords: Tree rings, dendrochronology, *Quercus macrocarpa* Michx., *Quercus bicolor* Willd., subfossil wood, Missouri, Iowa, Holocene.

INTRODUCTION

Multi-millennium tree-ring chronologies are a pillar of dendrochronology and other sciences. They have shown enormous potential with many types of applications, including development of the radiocarbon calibration curve, high-resolution reconstructions of paleoenvironmental conditions (*e.g.* climate, fire, frost, streamflow, flood) (Schweingruber 1996), archaeological and geological dating, and elucidation of the extent, timing and frequency of global-scale events (*e.g.* earthquakes, volcanic eruptions) (Baillie 1995). Developing multi-millennium length tree-ring chronologies and combining them with other climate proxy data are increasingly common and important objectives of current paleoenvironmental research (Hughes 2002).

A recent query of the International Tree-Ring Databank (ITRDB) (http://www.ncdc.noaa.gov/paleo/treering.html [accessed Feb 9, 2009]) resulted in eighty-seven millennium-length tree-ring chronologies constructed worldwide. In the United States, fifty-nine tree-ring chronologies are >1,000 year in length, with most of these (n = 54) from the western United States where long-lived species (*e.g. Pinus longaeva* D. K. Bailey, *Pinus flexilis* James, *Pseudotsuga menziesii* (Mirb.) Franco) readily provide long tree-ring records (Figure 1). Conversely, in eastern North America (east of 95°W longitude), only five tree-ring chronologies exceeding 1,000 years are listed in the ITRDB, four developed from baldcypress (*Taxodium distichum* [L.] Rich.) in wetlands (Stahle *et al.* 1988) and one from subfossil white pine (*Pinus strobus* L.) (Guyette 1996). Long chronologies other than those listed on the ITRDB likely exist (*e.g.* eastern white cedar [*Thuja occidentalis* L.]) (Buckley *et al.* 2004), but we know of no chronologies from eastern North America that are either multi-millennium or date to the B.C. period.

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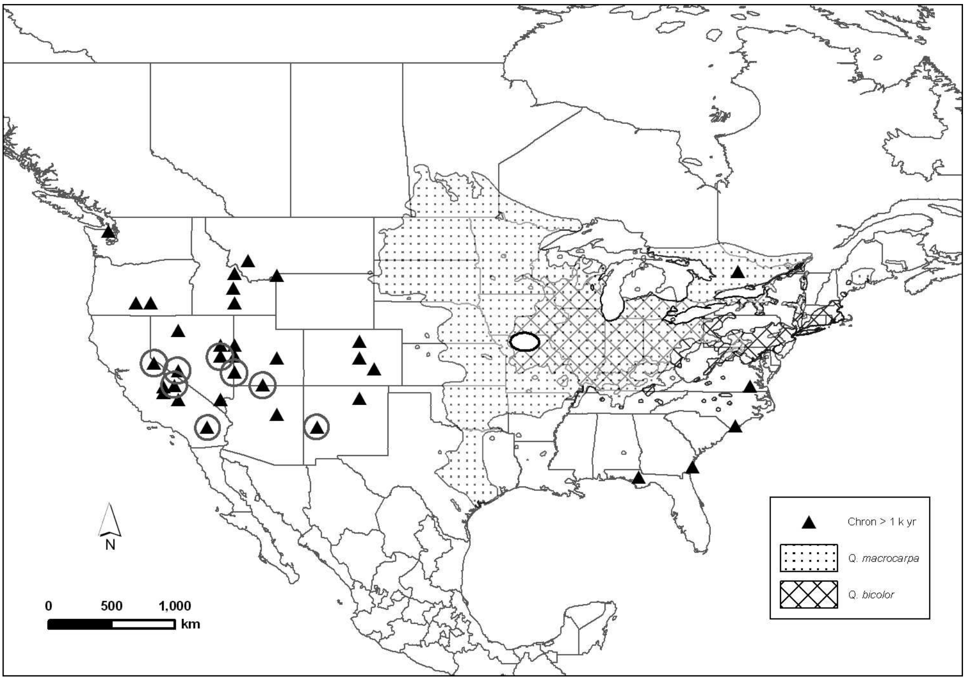

Figure 1. Map of North America showing the study area (white ellipse) within the ranges of bur oak (*Quercus macrocarpa*) (stippled area) and swamp white oak (*Quercus bicolor*) (crosshatched area) after Little (1971). A very large ecological amplitude may account for the continuous presence of bur oak through the Holocene period (*i.e.* along its 2,700 km north-south distribution annual mean minimum temperature varies by 25°C and annual precipitation varies by 100 cm. Black triangles are approximate locations of 1,000+ year long chronologies and circled black triangles are chronologies >2,000 years in length (source: International Tree-Ring Databank (ITRDB) (http://www.ncdc.noaa.gov/paleo/treering.html [accessed June 4, 2008]). Locations of chronologies are to nearest degree and may not precisely locate collection sites. Multiple chronologies may exist at a given triangle.

Globally, pine (*Pinus*) and oak species constitute the majority of millennial chronologies. Compared to the longest-lived trees, oaks are relatively short-lived (*ca.* 350 years), so millennium tree-ring chronologies require inclusion of historical and subfossil wood. Multi-millennium oak chronologies have been constructed from several areas of Europe (Baillie 1995; Krapiec 2001; Leuschner *et al.* 2002), but none have been constructed in North America. Relatively recent efforts by St. George and Nielsen (2002) have shown the potential for developing long oak chronologies from southern Manitoba. Pollen records suggest the temporal depth of these chronologies could extend back to *ca.* 8,000 cal yr B.P. (Williams *et al.* 2004). In the central US, approximately 1,500 km south of southern Manitoba, oak pollen data (Delcourt and Delcourt 1987) and subfossil trees suggest the genus has been continuously present for at least the last 15,000 years, even during extreme climate periods (*e.g.* Hypsithermal, Younger Dryas).

Compared to western US chronologies, tree-ring chronologies from the Central US have had little information to bear on Holocene climate and tree-growth variability. Central US chronologies are severely limited in temporal depth and rarely exceed 400 years in length. Long tree-ring records from the western and southeastern US are of limited utility for understanding central US climate variability because of major differences in oceanic and continental influences. Our work shows that potential exists for developing a millennium-length tree-ring chronology in the central US, which would be particularly valuable considering the regional limitations (Woodhouse and Overpeck 1998), the paucity of long chronologies, the distance from other similar data, and the continental location (Guyette *et al.* 2006). In addition, because these chronologies exemplify

Figure 2. Worker pulls a canoe up the Thompson River (Missouri) where multiple stems of subfossil oak wood protrude from the cutbank along a cornfield. Stream banks can erode several meters per year, which facilitates the excavation of new wood. Thousands of kilometers of streams exist in the region of northern Missouri and southern Iowa.

long-term variability in plant growth, they may have important societal implications considering the value of the surrounding agricultural region to global economies and the uncertainty for the future of these economies in light of recent and projected changes in climate and commodity trends (Reilly *et al.* 2001). Though still in the early stages of development, progress so far on the American Long Oak Chronology (ALOC) shows excellent potential for lengthening the annual-resolution climate proxy available for this region by 10 to 40 times its current length.

METHODS

Study Site

In 1999, subfossil oak logs (aged 300 to 14,000 cal year B.P.) were found in streams of Missouri, U.S.A., now fully recognized as an exceptional and abundant subfossil wood resource (Figure 2) (Guyette *et al.* 2008). The actively meandering streams at the Missouri-Iowa border region flow though an agriculturally dominated landscape that is ideally suited for the recovery of subfossil wood. Stream channels and banks are composed of alluvial sediments (silt, sand, clay) with low hydraulic resistance, allowing for frequent burial and excavation of wood (Brown 1997; Guyette *et al.* 2008). With each flood event new material is exposed in the banks and bottoms—a stream reach sampled one year may have a new set of wood of different ages one to three years later depending on the frequency and magnitude of flooding. Streams in this region occur in various conditions from relatively unaltered and meandering to highly altered and straightened channels with levees.

Once at the heart of the prairie parkland ecosystem, the landscape of the Missouri-Iowa border region today is predominantly an agricultural landscape, with corn and soybean fields often extending to the very edge of streams. Forests are still found along streams and rivers, though current species composition has shifted from historic composition, with species such as oaks being replaced by others such as elm (*Ulmus*) and hackberry (*Celtis*) (Nigh and Schroeder 2002). Oaks (*Quercus*) offer the best opportunities for developing long tree-ring chronologies. Bur oak, in particular, likely has the ability to withstand dramatic climatic changes based on its large ecological amplitude and range (Figure 1). Oaks are relatively heavy and are more slowly transported downstream. Finally, a large body of dendrochronological data, literature, and expertise exists for oak species.

Sample Collection, Condition, and Archival Storage

Subfossil oak is identified by several visual and physical properties (Nilsson and Daniel 1990; Schniewind 1990). Subfossil oak often has a gray to near-black exterior hue (Figure 3), whereas subfossil wood of other species commonly has brown hues. Because of oxidation of phenolic compounds, the interior of oak begins turning blackish-purple after 200 to 400 years of burial and becomes dull and completely black after several thousand years. The wood commonly has a unique exterior surface texture, including longitudinal grooving and exaggerated longitudinal and radial cracking, resulting from exposure after being buried in low oxygen environments for long time periods. The density and structural integrity of oak wood and tree rings generally decrease with age (Guyette and Stambaugh 2003).

Anatomical features such as ring porous wood, large rays, and abundant tyloses in early-

Figure 3. Photograph of recently collected subfossil oak sample MED697 that was tree-ring dated with the modern master chronology. Tree-ring series spans years A.D. 1158 to 1351. Though shown in grayscale the wood color is near to its true hue.

wood vessels identify oak wood to be collected. Although genera other than oak (*e.g.* subfossil *Ulmus*, *Fraxinus*, *Populus*) are encountered, they are seldom collected because of their more limited utility in crossdating and climate reconstruction. Currently, eight species of oaks occur within the study area; however, only bur oak (*Q. macrocarpa* Michx.) and swamp white oak (*Q. bicolor* Willd.) are important in riparian areas where trees have the potential to be recruited into streams and buried. Generally, only wood with more than approximately 100 rings is collected so as to facilitate tree-ring crossdating, though pieces with fewer rings are collected if they appear extremely old.

Cross-sections of subfossil logs are collected using a chainsaw and transported using canoes. Cores from live bur and swamp white oak trees have also been collected from throughout the study area. Sample locations are documented using a GPS, and sample condition (*i.e.* size, orientation, submergence, burial context) is recorded and photographed. This represents the only permanent record of the site condition and location because the wood is often removed with subsequent flooding. Samples are sealed in plastic bags and transported to the Missouri Tree-Ring Laboratory where they are prepared for dating, measurement and archiving. Small blocks (*ca.* 20–30 g, 10 rings) of each sample are removed from the outer edge of the sample for density dating and radiocarbon dating purposes. Samples are washed, placed in plastic bins and stored in a cold room at 4°C until ring-width measurements are made. Following measurement, samples aged approximately <4,000 cal yr B.P. are placed in dry storage while samples >4,000 cal yr B.P. are vacuum sealed in plastic bags and placed in cold storage. We hope these methods prolong the preservation of our subfossil oak samples, which when wet are prone to degradation by drying and fungi.

Chronology Development

The greatest challenge in dating samples is to avoid false matches. Because the potential dating period is at least 14,000 years in length and individual samples are 100 to 300 years long, they must be stratified by age to reduce the potential for false matches. We utilize three dating methods to foster the efficient and accurate development of chronologies: density dating, radiocarbon dating and dendrochronological dating. Density dating, using a regression equation previously developed by the authors (Guyette and Stambaugh 2003), provides a quick but coarse estimate of sample age and enables selection of samples most suitable for radiocarbon dating.

Radiocarbon dating is conducted on acid-alkali-acid-treated wood samples by independent commercial laboratories (Geochron Laboratories; Beta Analytic, Inc.), which provide radiometric measurements of ^{14}C content and radiocarbon ages. Ages are based upon the Libby half-life (5,570 years) for ^{14}C and corrected for isotopic ($^{13}C/^{12}C$) fractionation. CALIB Version 5.0 software (Stuiver and Reimer 1993) and the INTCAL04 calibration data set (Reimer *et al.* 2004) are utilized to calibrate conventional radiocarbon ages.

Tree-ring series from at least two radii of each sample are measured to 0.01 mm precision and quality control checks of measurements are made by comparing the ring-width plots and reviewing ring-width patterns on the wood. Freezing, painting, razor trimming and other specific surfacing techniques have been sufficient to permit the measurement of oak tree rings up to 13,818 cal year B.P. in age. Ring-width measurement files are organized in groups based on similar carbon dates. Once twenty or more series occur in a ^{14}C group of less than 500 years, we then begin using a "kernel" approach to developing a chronology. The approach has 4 steps:

1) Potential samples for the "kernel" (*i.e.* beginning) of a chronology are identified based on the length of the ring-width series (*e.g.* >200 years), quality control checks of measurements, and high signal-to-noise variance characteristics (*e.g.* high mean sensitivity, minimal suppressed growth).
2) Statistical suggestions of multiple dating possibilities are the beginning point for inspecting crossdating potential. For example, samples occurring in a temporal cluster (*e.g.* radiocarbon ages between 2,000 and 2,500 cal yr B.P.) undergo correlation analysis to provide interseries correlations and Student's t-tests[1] between all series using Program COFECHA (Holmes *et al.* 1983; Grissino-Mayer 2001). T-scores are required to suggest that chance ring-width matches had a probability of occurring less than 1 in 1,000 times. T-scores above 6.0 are (in practice) needed for developing the "kernel" of a chronology[2].
3) Visual determination of signature years using graphical ring-width or skeleton plots are the starting point for crossdating attempts (Baillie 1995). When present, ring anomalies (*e.g.* enlarged latewood vessels, frost rings, flood rings; Yanosky 1983) also aid in validating crossdated samples. Cores from live trees are used to absolutely date the modern chronology, and a nearby published reference chronology from Iowa (Duvick 1996) was used to check the dating accuracy back to *ca.* A.D. 1600.
4) Construction of "kernel" chronologies begins with oak samples with the best visual pattern-matching of ring-width plots, matching of wood features, and statistical verification results. Initial chronology construction progresses slowly and cautiously utilizing many dating checks such as: review of carbon dates, comparison of wood condition (*e.g.* color, density), iterative replacement and removal of series to test the stability of statistical results, and, if possible, comparison against regional tree-ring chronologies. No missing rings have been added in chronology construction or detected in cores from living trees.

For the purpose of displaying the time series properties of the modern (A.D. 912–2004) chronology we developed a raw, standardized, and regional curve standardization (RCS) chronology. Ring-width measurements were detrended and standardized using program ARSTAN (Cook and Kairiukstis 1990; http://www.ldeo.columbia.edu/res/fac/trl/public/publicSoftware.html). A raw ring-width chronology represented the annual mean ring width. A standardized ring-width chronology was developed by detrending ring-width series with a negative-exponential or straight-line. Individual indexed series were combined into a chronology by computing a bi-weight robust mean. An RCS chronology was developed by using a single pith aligned mean growth curve as the detrending function. Running interseries correlations (Rbar) and the expressed population signal (EPS) (Wigley *et al.* 1984) were computed for 50-year time periods with a 1-year time step.

CURRENT PROGRESS

Over 550 samples of subfossil oak wood have been collected to date. Radiocarbon dates have been obtained for over 330 of these. This collection of wood has yielded one absolutely dated chronology and six other floating chronologies that combined, cover approximately 2,781 years of the Holocene.

1,000-Year Master Chronology

A 1,093-year-long absolutely dated master tree-ring chronology spanning A.D. 912 to 2004 has been developed from 144 oak samples (49 live, 95 subfossil) (Table 1, Figure 4, and Supplementary

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[1] Ring-width measurements ran as undated series in COFECHA

[2] Based on crossdating results between live trees and trees recently recruited and buried in the stream, a mean between-tree correlation coefficient of 0.56 for a 100-year period will allow for statistical validation of ring-width matches at a probability of greater than 0.00001 within groups.

Table 1. Characteristics and COFECHA output of the subfossil oak tree-ring chronologies developed to date.

Chronology Name	Absolute Modern	Floating					
		1800 B.P.†	2300 B.P.	3500 B.P.	4000 B.P.-chron2	4500 B.P.	11000 B.P.
Period of Record *or* Range of ^{14}C ages*	AD 912–2004	1730–2130	2330–2780	3460–4400	3680–4400	4750–4760	11150–11340
Years of record	1093	407	273	312	271	101	324
Number trees	144	20	13	12	6	3	12
Number of dated series	258	40	27	23	12	7	25
Total rings in all series	35564	5858	4099	3869	2197	530	3614
Series intercorrelation	0.51	0.50	0.49	0.49	0.53	0.60	0.57
Average mean sensitivity	0.21	0.20	0.17	0.21	0.20	0.24	0.24
Mean autocorrelation (unfiltered)	0.39	0.68	0.74	0.66	0.74	0.39	0.62
Mean length of series (years)	137.8	146.4	151.8	168.2	183.1	75.7	144.6
Average segment correlation range	0.39–0.58	0.38–0.59	0.34–0.54	0.41–0.58	0.50–0.62	0.59–0.74	0.53–0.71
Segments flagged, possible problems	7 (6 B's, 1 A)	3 (A's on 2 samples)	2 (B's on 1 sample)	5 (4 B's and 1 A)	0	0	1 (B)

All COFECHA statistics based on 80-year segment length, 40-year lag.
*intercept with radiocarbon curve (cal yr B.P.).
†"B.P." refers to cal yr B.P.

Material). Average interseries correlation is 0.51 and allows for statistical validation of tree-ring series as short as 80 years (Supplementary Material). Using COFECHA with the chronology segment length examined set at 80 years (lag 40), all correlations of series exceed the critical correlation (99% confidence interval) with 7 of 558 segments flagged for possible problems. Mean chronology segment correlations range from 0.39 to 0.58. Series with less than 80 years only come from live trees. From A.D. 1000 to present the years of the smallest standardized ring-width index value per century listed in increasing index order were: 1062, 1874, 1556, 1934, 1698, 1104, 1728, 1239, 1348, and 1411.

The raw ring-width chronology shows mean ring widths are fairly constant for the period of *ca.* A.D. 1080 to 1850 (Figure 4). Before this period the raw ring widths tend to be more variable because of low sample size (*e.g.* <20 series). After *ca.* 1850 raw ring widths tend to step up and be generally larger. Rbar and EPS values indicate that a common signal exists in the chronology from *ca.* A.D. 1000 to present with the exception of *ca.* 1830 to 1868 when values of both statistics are significantly decreased. The chronology during this period has somewhat decreased ring widths and sample depth. Causes for these effects are currently unknown, but the timing is generally coincident with an increased abundance of cores from live trees, the beginning of EuroAmerican settlement and land-use changes, and severe drought (Meko 1992; Muhs and Holliday 1995). St. George and Nielsen (2002) documented similar chronology statistics and characteristics during the same time period in southern Manitoba.

Calibrated ^{14}C ages are essential for chronology construction because crossdating potential significantly increases when these are available. Calibrated ^{14}C ages provide a relatively close approximation for actual ring dates. Differences between radiocarbon dates and outer tree-ring dates appear to be larger after A.D. 1500 than before (Supplementary material). For example, prior to A.D. 1500 five of twenty-nine (17%) actual ring dates fell outside of the two sigma range of ^{14}C calibrated results. However, after A.D. 1500 15 of 30 (50%) actual ring dates fell outside of the two sigma range of ^{14}C calibrated results. Reasons for the increased disparity between dates after A.D. 1500 are unknown, but we suspect the causes are

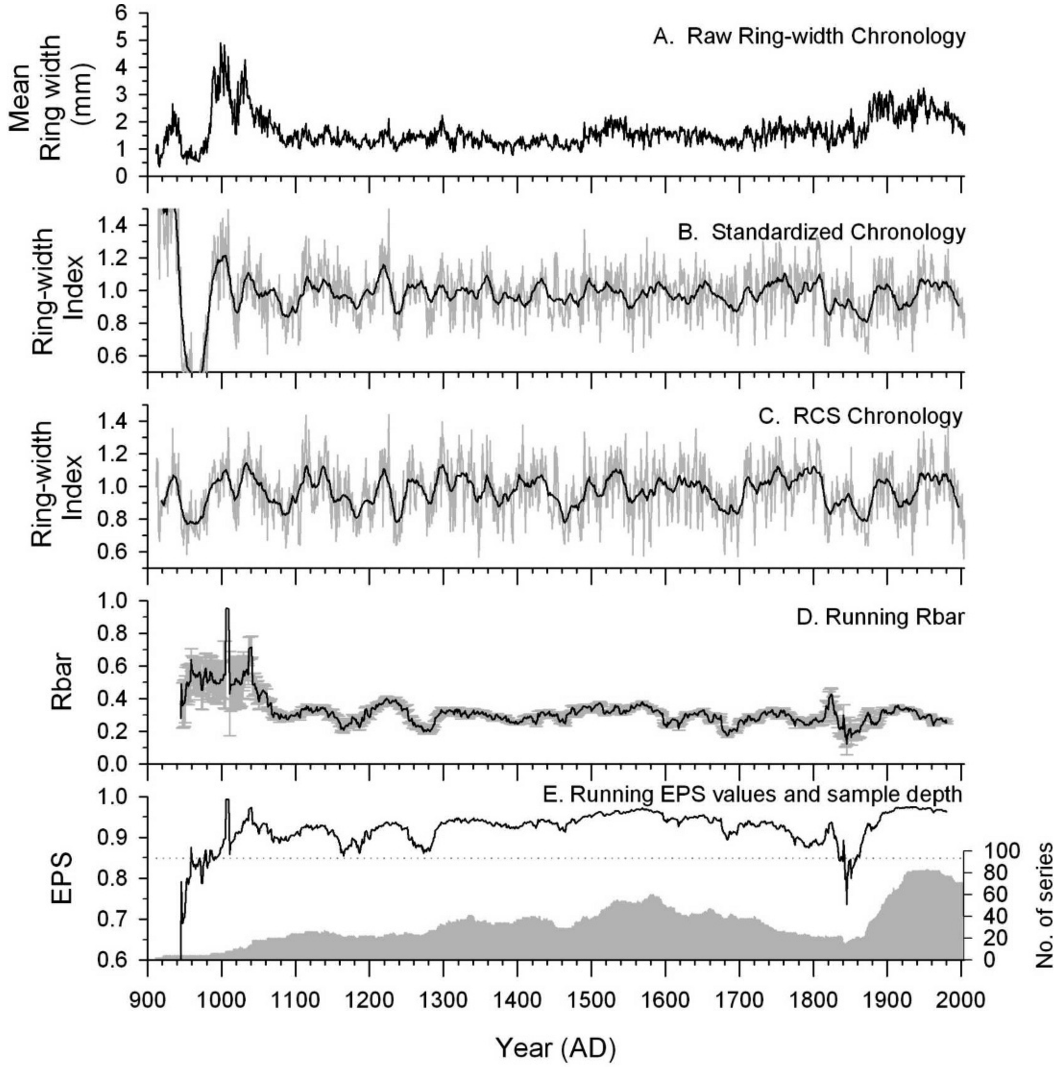

Figure 4. Graphs depicting time-series characteristics of the white oak (*Quercus macrocarpa*, *Q. bicolor*) total ring-width chronology for the period A.D. 912 to 2004 (see Supplementary Material Table 1). (A) Raw ring-width chronology of annual mean ring-width values, (B) standardized ring-width chronology showing annual indices (grey) and 15-year moving average (black), (C) regional curve standardization (RCS) chronology showing annual indices (grey) and 15-year moving average (black), (D) running series average correlation (Rbar) (black) (Wigley *et al.* 1984) with grey bars representing two standard errors. (E) Expressed population signal (EPS) (black) with sample depth (grey). Rbar and EPS were calculated using a 50-year moving interval with 1-year step.

related to radiocarbon measurement errors in the laboratory or the fact that the calibration curve during this period fluctuates around a fairly constant level (Blackwell *et al.* 2006).

Development of the master chronology has decreased our need to carbon-date samples under *ca.* 1,000 year in age. If samples are high in density and have physical features similar to that of samples dating to the last 1,000 years, crossdating attempts precede carbon dating. New trees are added to the master chronology with nearly every sample collection trip (Figure 4), statistically strengthening the chronology with each sample addition.

Floating Chronologies

In addition to the 1093-yr absolutely dated chronology, several "floating" chronologies are

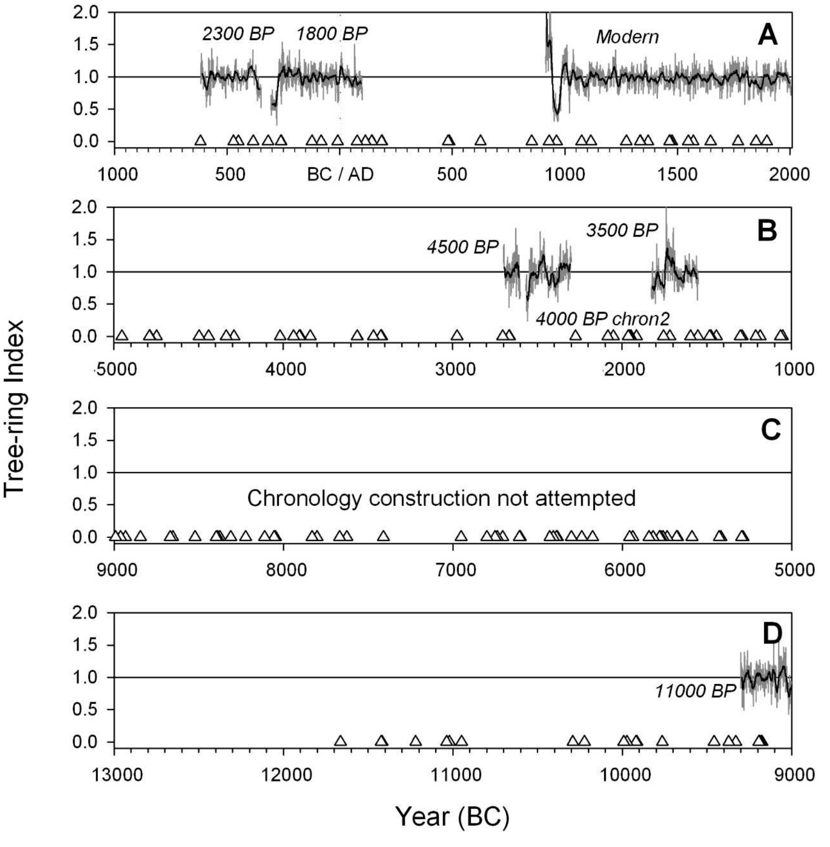

Figure 5. Standardized tree-ring chronologies developed from buried subfossil oak wood recovered from streams flowing through southern Iowa and northern Missouri, U.S.A. A continuous period of the late-Pleistocene and Holocene are shown in four panels: (A) 1000 B.C. to present, (B) 5000 to 1000 B.C., (C) 9000 to 5000 B.C., and (D) 13000 to 9000 B.C. Chronology names are given in italics and coincide to those described in Table 1. Triangles represent oak samples that have been radiocarbon dated but not yet incorporated into existing chronologies or developed into new chronologies. "B.P." labels refer to cal yr B.P.

also being constructed (Table 1, Figure 5). These chronologies are approximately located in time according to radiocarbon dates. These and other floating chronologies are in the early stages of development and constantly evolving to include more samples as they become available. We are currently focusing on connecting the 407-yr long chronology (dated at *ca.* 500 B.C. to A.D. 200) to the absolutely dated master chronology, and also on further development of the 324-yr-long chronology at *ca.* 9000 B.C., which may reveal new information about the Younger-Dryas stadial. Recent collections of early Holocene–late Pleistocene conifers expatriated from northern Missouri may also aid in developing chronologies through this period. The oldest tree found to date is a tamarack (*Larix laricina* (Du Roi) K. Koch) with a measured radiocarbon age of 22,500 ^{14}C yr B.P.

FUTURE WORK AND CHALLENGES

We are currently in our eighth year of sample collection, chronology development and analysis. Based on our progress so far, we believe that multi-millennial chronologies from subfossil wood in the central United States are inevitable. Information on the temporal distribution of oak wood indicates that a continuous tree-ring chronology spanning 12,000 years or more may be possible in northern Missouri and southern Iowa. Presently, temporal gaps result from low sample size and a limited radiocarbon dating budget. At this stage of our research we do not know how gaps and clustering in the temporal distribution of sample oaks will affect our chronology construction or whether gaps in the tree-ring record are caused by changes in oak abundance. Other workers (*e.g.* Becker 1981) have overcome low abundance of samples during certain periods of record by continued collection spanning many years and many sites. Even if permanent temporal gaps in the tree-ring record exist, wiggle-matching (Baillie 1995) of high precision carbon dates and the ^{14}C record can allow for dating of floating chronologies to within a few decades. Other challenges also exist such as identification of the climate signal and determination of how it may have varied over millennia. In addition, the segment length of series, which for oaks can be relatively short (*e.g.* 100 to 250 years), is a limit of the chronology's utility for extracting low-frequency signal (*i.e.* "segment length curse") (Cook *et al.* 1995).

From the current chronology progress we have proven that construction of multi-millennium oak chronologies is possible in the US. These chronologies could potentially span the Holocene period and be combined with other very long tree-ring records developed in the United States, Europe and elsewhere, which are used to assess global scale climate changes. Furthermore, these data will complement other Central US region paleoclimate data and aid in understanding historic climate dynamics in an important agricultural region.

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