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A 1400-YEAR BØLLING-ALLERØD TREE-RING RECORD FROM THE U.S. GREAT LAKES REGION

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ABSTRACT

Since the late 19th Century, geologists and naturalists working in the US Midwest have reported an abundance of tree macrofossils embedded in glacial and lacustrine deposits formed after the Last Glacial Maximum. The most widely-known of these sites is the Two Creeks type locality in Wisconsin. We report progress on development of a long tree-ring record from this subfossil wood in the US Great Lakes region, employing samples collected during a decade-long series of field campaigns at recently eroded lake shorelines, construction projects, and excavations, along with acquisition of archived samples collected from the 1950s to the 1980s during past lake erosion events. A previously-reported tree-ring chronology from the Two Creeks type locality reached *ca*. 250 years in length; here we used radiocarbon dates and tree-ring crossdating to develop a 1408-year tree-ring chronology (mainly spruce [*Picea* spp.] with some tamarack [*Larix*]) comprising a total of 135 overlapped tree-ring width series in three clusters from nine locations in eastern Wisconsin. The calendar age of the record is estimated with 46 ^{14}C dates to between 14,500 to 13,100 cal BP. This is currently the oldest and only long tree-ring record in North America from the boreal environments of the Bølling-Allerød warm period during the transition from the Late Glacial to the Holocene.

Keywords: dendrochronology, radiocarbon, Two Creekan, Older Dryas, deglaciation, abrupt climate change.

INTRODUCTION

The first major warm interval following the Last Glacial Maximum is known as the Bølling-Allerød, *ca*. 14,500 to 13,000 years ago (Mayewski *et al*. 1993), which terminated with the onset of the cold Younger Dryas Event. The sustained Bølling-Allerød warmth was occasionally interrupted by abrupt excursions such as the Older Dryas (*ca*. 14,000 years ago) and the Intra-Allerød cool periods (*ca*. 13,100 years ago) (Grootes *et al*. 1993; Stuiver *et al*. 1995). Our knowledge about this period is largely informed by Greenland ice cores and sediment/pollen records on both sides of the North Atlantic, although tree rings could provide an added high-resolution perspective on the environment during this period.

On the east side of the Atlantic, a 12,000-year tree-ring chronology has been constructed based on a 10,000-year oak chronology extended by an additional 2000 years with a pine chronology (Friedrich *et al.* 2004; Kaiser *et al*. 2012). Older wood has been found, which radiocarbon dates back to Bølling-Allerød (Kaiser 1972, 1994; Suess 1979; Friedrich *et al.* 2001), but the chronologies are "floating", *i.e.* pre-dating the 12,000-year chronology, so that rings of the Bølling-Allerød wood do not have exact calendar dates (Kaiser *et al*. 2012).

On the west side of the Atlantic, the development of a continuous chronology back to the Bølling-Allerød in North America is less advanced. A tree-ring chronology of bristlecone pine from the White Mountains of California extends back over 8800 years to the early Holocene (Ferguson 1969; Ferguson and Graybill 1983). In the mid-continent Great Lakes region, an absolute oak chronology centered on the state of Missouri extends back from the present a little over 1000 years, with the promise of extending it using subfossil oak logs that date as far back as 11,000 to 12,000-years old

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(Stambaugh and Guyette 2009). A chronology exceeding 2780 years was developed with eastern white cedar from the Niagara Escarpment (Flowerport Island) in southern Ontario (Buckley *et al.* 2004).

Although these chronologies do not yet reach the Bølling-Allerød, ancient wood of Bølling-Allerød age has been preserved at several sites in the Great Lakes associated with glacial till, lake sediment and peat deposits, the most notable of which is the Two Creeks type locality in Wisconsin (Wilson 1932; Black 1970; Mickelson *et al.* 2007). Black (1970) first mapped the widespread distribution of Two Creeks-age organic matter (including wood) in eastern Wisconsin. Kaiser (1994) was able to construct a 252-year floating tree-ring chronology from the Two Creeks site, establishing a minimum duration for the interval. A longer 310-year floating Two Creeks chronology was developed by Panyushkina and Leavitt (2013), along with post-Two Creeks Preboreal and mid-Younger Dryas-age spruce records of at least 120 years in length (Panyushkina *et al.* 2008; Panyushkina and Leavitt 2013). A much longer period of boreal forest occupation is suggested in the range of radiocarbon dates of wood from the Two Creeks site obtained by Suess (1979) and in the gastropod analysis of Rech *et al.* (2012), which indicates presence of taiga for at least *ca*. 1000 years beginning *ca*. 14,500 cal BP.

We have assembled tree-ring records from a large collection of subfossil wood samples from nine locations (Figure 1) in eastern Wisconsin preserved by the post-Two Creekan readvance of the Green Bay and Lake Michigan ice lobes of the Laurentide Ice Sheet during the Older Dryas and by other favorable environments in adjacent areas during the Bølling-Allerød interval. The goal was to use dendrochronology and radiocarbon dating to crossdate the wood and establish a calendar-age framework for the floating sequences in order to develop a long tree-ring chronology from the Bølling-Allerød interval in the North American mid-continent. This effort is a necessary first step in establishing a long record suitable for future paleoclimate and environmental research.

THE SITES

Wood specimens have been obtained from a number of sites that contain macrofossils whose radiocarbon ages signify the presence of forests during the Bølling-Allerød interval (Figure 1). Most specimens were sampled during a decade-long series of field campaigns from recently-eroded lake shorelines, construction projects and excavations (Panyushkina and Leavitt 2010). Other specimens were acquired from museum and private archives collected from the 1950s through the 1980s during past lake erosion events. The 11 sites contributing to the chronologies described in this paper are as follows:

- GB: Peter's Quarry, Nicolet Road, in Green Bay, Wisconsin, from a 1958 wood collection of Hugh Iltis (University of Wisconsin botanist) provided by Klaus Westphal (emeritus University of Wisconsin Geology Museum Director),
- PF: Paris Farm, Kenosha County, Wisconsin, collected by the authors in 2013–2014,
- JD: Two Creeks type locality (Wisconsin) collected by Charles Schweger (University of Alberta) in 1952 and archived at the University of Arizona,
- JF: Jorgensen Farm, Waushara Co., WI, collected by the authors in 2005,
- ND: New Denmark, WI, collected by Ron Stieglitz and Joe Moran (University of Wisconsin-Green Bay geoscientists) in 1980s,
- DC: Pond Excavation at Brussels, Door Co., WI, collected by Ron Stieglitz and Joe Moran (University of Wisconsin-Green Bay geoscientists) in 1990s,
- TC: Two Creeks type locality (Wisconsin) collected by the authors between 1985 and 2005,
- WF: Two Creeks type locality (Wisconsin) collection by Wes Ferguson (University of Arizona dendrochronologist) *ca.* 1958,
- AH: Detention pond excavation on southeast side of Green Bay, WI, collected by the authors in 2004,
- LB: Highway construction near Lake Butte des Morts, west of Oshkosh, WI, collected by the authors in 2011,
- OC: Outagamie County, east of Appleton, WI, collected by the authors in 2011, 2015 and 2016.

The samples and data from Kaiser (1994) were not available for this study. Additional details

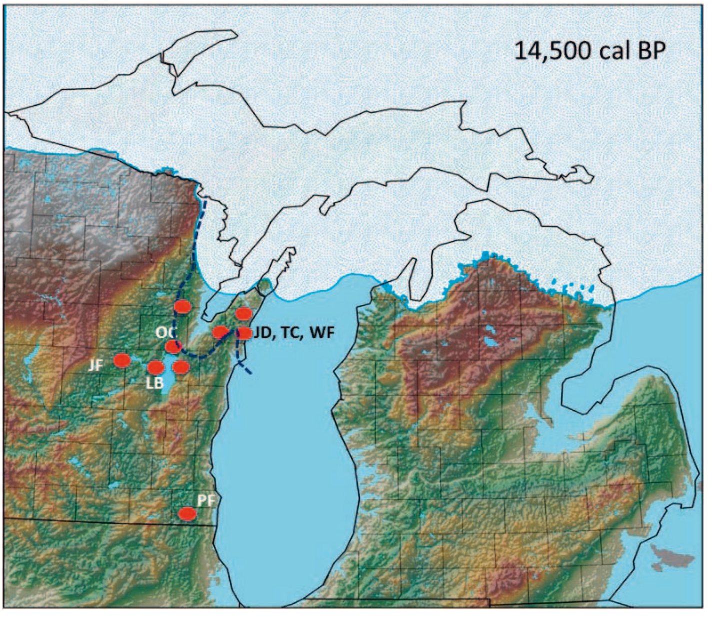

Figure 1. Map of the Lake Michigan area locating the sample sites (red dots). The Laurentide ice sheet position is shown during a period of ice recession (*ca*. 14,500 cal BP) that opened up the terrain where the boreal trees became established, and the post-Two Creekan final ice advance, *ca*. 13,000 cal BP (dashed line), buried some of the sites. [The map is courtesy of Randall Schaetzl, Michigan State University.]

and map locations of these sites are given at http://greatlakes.ltrr.arizona.edu/.

METHODS

Subfossil wood collected in the field or subsampled in the archives was cut in disks, wrapped in clear plastic to preserve fresh surfaces for ring analysis particularly when the wood was wet, and shipped to the Laboratory of Tree-Ring Research, University of Arizona. Wet surfaces were planed with fresh razor blades to reveal clear microanatomy just prior to ring-width measurement. Disks from dry wood were polished with sand paper following the standard procedure of sanding with progressively finer grit. For wood specimens that had more than 50 rings, tree-ring width series were measured on Lintab or Henson measurement systems (0.01-mm precision).

Subsamples were taken for wood taxonomy identification and ^{14}C dating. Diagnostic wood anatomy analysis was performed at the USDA Forest Product Lab in Madison, Wisconsin. For ^{14}C dating, 10-year ring-group samples were obtained from outer rings or inner rings of selected specimens, ground to 20-mesh, and processed to α-cellulose (occasionally holocellulose) using the Jayme-Wise method modified after Leavitt and Danzer (1993). The cellulose samples were analyzed at the NSF-Arizona Accelerator Mass Spectrometry (AMS) Laboratory at the University of Arizona. Many of the wood samples previously collected by other investigators already had ^{14}C dates determined at established radiocarbon labs in the US, typically after acid-alkali-acid pretreatment of the wood. To achieve the highest possible accuracy of calibration results, we included two trees (TCSL-71A and TCIP-12A) in our analysis, which were used for wiggle-match dating of the Two Creeks site (Leavitt *et al.* 2007). Radiocarbon wiggle-matching fits the radiocarbon pattern from the successive ring groups of the wood sample to the master radiocarbon calibration chronology for more accurate age assignment than from a single radiocarbon age alone. Radiocarbon ages were calibrated using the Calib 7.1 program and the IntCal13 calibration curve (Reimer *et al*. 2013). The ages reported herein use calibrated ^{14}C years before present (AD 1950), which we denote as 'cal BP'. Wiggle-matching of the ring sequence from TCSL-71A and TCIP-12A

Table 1. Statistics of ring width series (raw measurements) at each site arranged according to age clusters determined with radiocarbon dating. Cluster statistics are shown in bold. Details on site locations and wood collections are presented at http://greatlakes.ltrr.arizona.edu.

Site ID	Site Name	Series (trees)	Span (year)	R	St. Dev.	Coordinates*
Cluster 1		***32***	***511***	***0.50***	***0.30***	
GB	Green Bay	19	417	0.54	0.30	N44.30480 W88.0570
PF	Paris Farm	6	121	0.43	0.29	N42.63757 W88.01390
JD	Two Creeks	7	218	0.51	0.30	N44.32538 W87.54524
Cluster 2		***77***	***684***	***0.44***	***0.29***	
JF	Jorgensen Farm	5	173	0.44	0.25	N44.16425 W88.91306
ND	New Denmark	12	143	0.41	0.31	N44.37123 W87.80616
DC	Door County	2	198	0.36	0.20	N44.15560 W87.6100
TC	Two Creeks	29	295	0.40	0.24	N44.32538 W87.54524
WF	Two Creeks	10	166	0.43	0.40	N44.32538 W87.54524
AH	AmeriHost	19	293	0.44	0.30	N44.52460 W88.06570
Cluster 3		***26***	***214***	***0.47***	***0.30***	
LB	Lake Butte des Morts	15	166	0.48	0.28	N44.03886 W88.58842
OC	Outagamie Landfill	11	149	0.48	0.31	N44.17390 W88.20270

R = inter-series correlations; *Decimal coordinates of latitude and longitude.

placed their growth at *ca*. 13,760–13,530 cal BP (Leavitt *et al*. 2007).

We first crossdated tree-ring width series of each separate collection at the sites, and then found overlaps between collections and sites in accord with radiocarbon dating. Visual matching of ring-width series, replication of time series, and statistical comparisons were taken into account for matching ring patterns (Stokes and Smiley 1996). The Pearson correlation and the Student t-test values were primary criteria for accepting matched patterns. The statistics for crossdated time series were calculated in the TSAP program (www.rinntech.com). Quality control of crossdated tree-ring series was confirmed with the COFECHA program (Holmes 1983).

The chronology of tree-ring widths was computed in the ARSTAN program (www.ldeo.columbia.edu/tree-ring-laboratory) using biweight robust mean that discounts the influence of outliers during the computing of the mean-value function (Mosteller and Turkey 1977). Detrending and index calculation were not performed in establishing the chronology.

RESULTS

Clusters of Crossdated Tree Rings

Tree-ring analysis of over 330 specimens of spruce (*Picea* spp.) and larch (commonly called tamarack, *Larix*) from 11 collections at nine sites resulted in development of 11 ring-width sequences consisting of a total of 135 crossdated series (Table 1), *i.e.* about 41% of the specimens. Sites include the Two Creeks type locality north of the town of Two Rivers (Manitowoc County), the Green Bay area (Waushara, Brown, and Winnebago counties) and Kenosha County, Wisconsin. The length of the 11 floating sequences varies from 121 to 417 years (Table 1). The number of matched series per site or collection varies greatly, from two up to 29 specimens. Even though the percentage of tree-ring series successfully crossdated is relatively low, the successfully matched series show a strong common signal and high variance (average std. dev. = 0.30). Average correlation of crossdated site series is about 0.42, significant at $p < 0.05$.

The matched site sequences were overlapped into three clusters using crossdating and radiocarbon dating (Figure 2). Table 2 illustrates the significance of matching statistics for the established overlaps. The length of overlaps varies from 50 to 198 years. The 50- to 74-year overlaps in the middle of Cluster 2 are relatively short, but the strength of the chronology is ensured by presence of other fitted sequences with longer overlaps during the interval and by the significant correlations of ring widths in all of the overlaps (Table 3). The range of calibrated ^{14}C ages (Supplementary Table S1) is consistent with the overlap placements. Cluster 2 includes

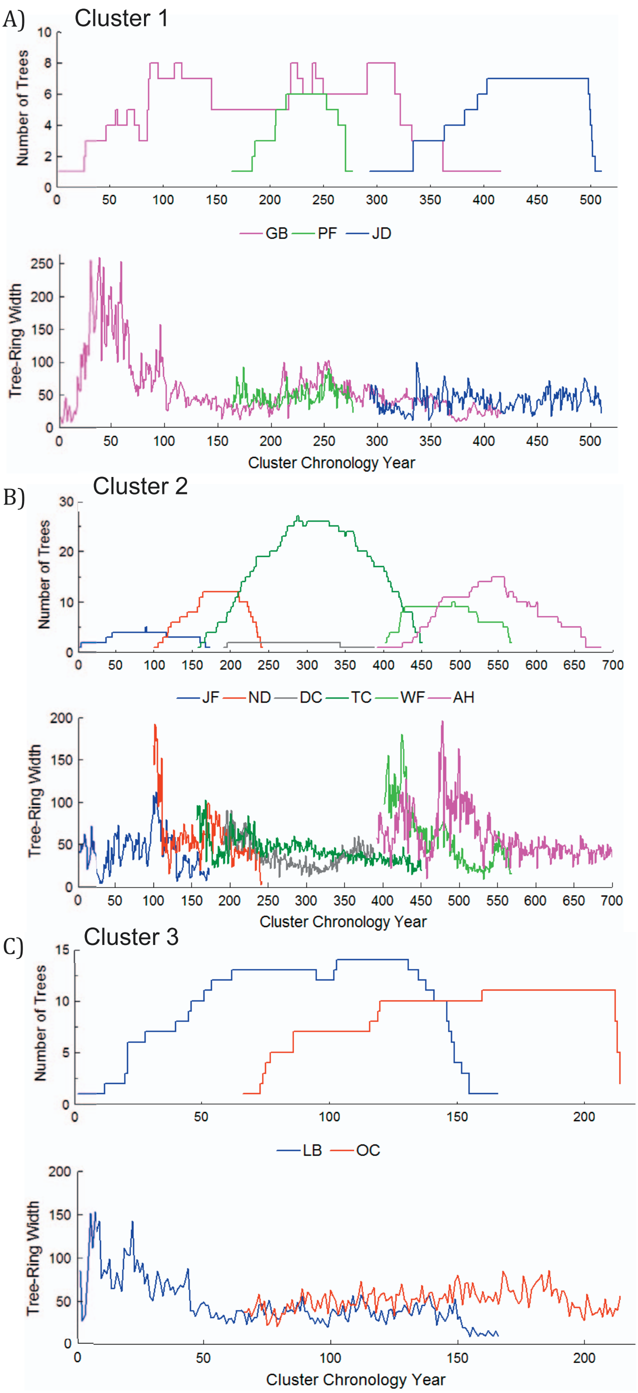

Figure 2. Site tree-ring chronologies overlapped within each age group (cluster): (A) overlap of three sites with the youngest ring *ca.* 14,000 cal BP, (B) six sites with outside rings at *ca.* 13,300 cal BP, and (C) two sites ending at *ca.* 13,100 cal BP. For each cluster, the top plot shows the number of overlapped trees, and the bottom plot is the mean ring-width chronology. Color of lines indicates site series listed in Table 1. Tree-ring widths are in mm [$\times 10^{-2}$].

Table 2. Statistics[1] of matching site series within the clusters calculated using the TSAP program. The longest series in clusters serve as reference series, and the number of years overlapping between each series and the references is given. Radiocarbon dates of wood from each site and collection determined the likelihood of possible overlaps.

Series	Position	Overlap	Glk-GSL	TV	TVBP	CDI
Cluster 1						
GB reference	1-417					
PF	155-275	121	66***	6.0	4.8	16
JD	295-417	123	61**	3.2	4.6	12
Cluster 2						
JF reference	1-173					
ND	100-242	74	63***	7.2	4.6	23
TC reference	156-450					
ND	100-242	87	73***	3.1	4.2	26
DC	191-388	198	68***	7.0	6.2	47
AH	392-684	59	68**	3.1	4.4	16
WF	401-566	50	70**	7.2	4.8	25
AH reference	392-684					
WF	401-566	166	62***	3.3	5.1	34
Cluster 3						
LB reference	1-166					
OC	66-214	101	65**	2.5	5.0	29

[1]Glk = Gleichlaeufigkeit coefficient, GLS = Gleichlaeufigkeit signature level, TV = t-Value, TVBP = T-Value Baillie-Pitcher, CDI = Cross-Date Index. Minimum matching conditions accepted: Glk >60%, GSL ≥70% (at least one *), TV >3.0, and CDI >10.

the two trees used in ^{14}C wiggle matching of the Two Creeks specimens (Leavitt *et al.* 2007), which firmly locates this cluster on the calendar time scale. Cumulative probability distributions of calibrated ages for multiple ^{14}C ages run on the tree rings identify the boundaries and calendar intervals of the cluster chronologies (Figure 3). Clusters comprise tree rings from 2 to 6 locations variously situated in eastern Wisconsin. The distance between overlapped locations within the clusters varies from 50 to 180 km (31 to 112 mi). The strong coherence of tree-ring patterns across this relatively large area (9000 km^2) suggests climatically-forced variations of the ring growth.

The structure and sample depth of the overlapped clusters is depicted in Figure 2. Cluster 1 consists of 31 time series of spruce (29 trees) and spans 510 years starting at *ca.* 14,500 cal BP. Cluster 2 comprises 75 series of spruce (70 trees) and spans 684 years from *ca.* 14,000 to 13,300 cal BP. Cluster 3 is a 214-year long record of based on 26 series of tamarak (19 trees) dated between 13,300 and 13,100 cal BP. The maximum number of series per year is 14 for Cluster 1, 28 for Cluster 2 and 18 for Cluster 3, which although not optimal, is sufficient for supporting the ring matches and providing robust well-dated chronologies.

The Bølling-Allerød Tree-Ring Record

By computing the mean of tree-ring width series of dated clusters, we developed a 1408-year

Table 3. Correlation between site chronologies overlapped within clusters. All correlations are significant at $p < 0.05$. Length of overlaps ranges from 50 to 198 year (see Table 2).

Chronology	PF	JD	JF	ND	DC	TC	WF	AH	OC
Cluster 1									
GB	0.26	0.22							
Cluster 2									
ND			0.27		0.30	0.28			
TC				0.28			0.42	0.59	
WF								0.19	
Cluster 3									
LB									0.42

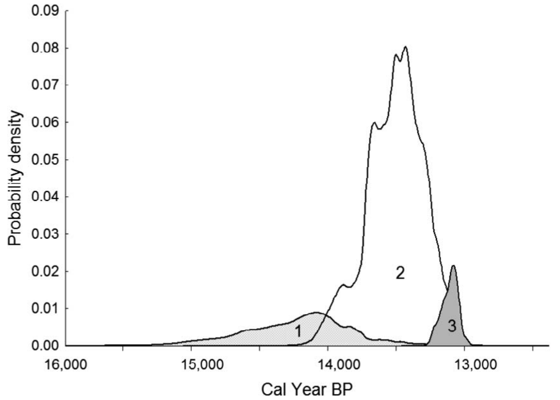

Figure 3. Calendar age of cluster chronologies estimated with the highest likelihood at 95% confidence intervals (2 sigma) of calibrated radiocarbon dates. Plots with marked cluster number are cumulative probability distributions calculated for clusters of radiocarbon dates shown in Supplementary Table S1. Position of overlapped time series (cluster chronology) in calendar time was accounted by the sharp boundaries and peaks of the ^{14}C sum distributions, and the ring crossdating of samples contributing to ^{14}C measurements. Number of radiocarbon dates per cluster: Cluster 1 = 3, Cluster 2 = 40, Cluster 3 = 3.

tree-ring width chronology spanning from *ca.* 14,500 to 13,100 cal BP (Figure 4). At this time, we do not have high confidence in attempting to overlap adjacent clusters, mainly because of the low replication of samples near the ends of each cluster chronology and the possible presence of overlaps that are simply shorter than 50 years, *i.e.* insufficient to bridge the cluster chronologies with high confidence. An example of a possible 23-year overlap between six time series of clusters 1 and 2 is given in Supplementary Materials (Table S2 and Figure S1). Hence, we opted not to connect the cluster chronologies, and the crossdating and thus the full record has, what we consider, two short gaps at *ca.* 14,000 and 13,300 cal BP. The length of gaps was nominally assigned as 10 years and although no crossdating was confidently identified between the clusters, the range of radiocarbon ages at the ends of adjacent cluster chronologies overlapped. We cannot exclude the possibility that differences in species may have impeded crossdating between Cluster 2 (spruce) and Cluster 3 (larch) if they actually overlapped. On the other hand, gaps of more than 10 years might be possible, but the current chronology already indicates a lengthy 1400 years of forest presence, *i.e.* much more than previously identified.

The sample depth varies greatly over the chronology length. Most segments of the record have over 10 trees at each point, except *ca.* 20-year periods at the ends of each of the cluster records with only 2–6 trees. The typical tree lifespans based on specimens with both pith and outermost rings in the chronologies were 144–155 years in Cluster 1, 120–177 years in Cluster 2 and 114–120 years in Cluster 3. Considerable variability and strong common patterns of year-to-year variation in ring

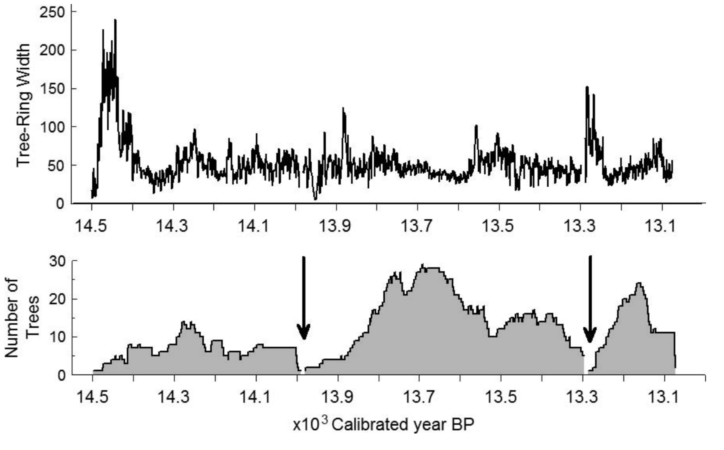

Figure 4. Composite tree-ring record of Great Lakes dated to the Bølling-Allerød period. Top: 1408-year composite chronology of tree-ring widths from three age-clusters of subfossil wood collected in Wisconsin. Bottom: Chronology sample depth. Vertical arrows show short gaps between three clusters discussed in the text.

widths between sites support sufficient bridging of tree-ring series from different locations into a long tree-ring record (Tables 1 and 3).

DISCUSSION

A remarkable cache of Bølling-Allerød wood from the Two Creeks type locality is being continuously exposed by erosion along the shoreline of Lake Michigan north of Two Rivers, WI. The standard stratigraphic profile of the type locality by Black (1970) depicts the forest bed (including stumps) underlain by lake silt and sand, and overlain by lake sand and then till, with logs in both of these deposits. Kaiser (1994) built a Two Creeks tree-ring chronology covering 252 years using 21 samples from the Two Creeks type locality, and estimated the forest was present for *ca*. 300 years. A companion 193-year chronology from a site near Appleton, WI, did not crossdate with the Two Creeks chronology, which Kaiser (1994) attributed to a microclimate different than that at Two Creeks. Although we did not have Kaiser's data to compare to ours, our millennium-length chronology gives credence to the possibility that Kaiser's chronologies were actually of different ages, and hence the lack of crossdating. A more detailed study of a 310-year tree-ring records at the Two Creeks type spruce forest at *ca*. 13,700 cal BP (Panyushkina and Leavitt 2013) concluded that multiple colonization events present during the glacial–postglacial transition were controlled to a greater extent by long-term rather than short-term temperature variability.

An extended presence of trees in the area is consistent with Mickelson *et al*. (2007) who estimated a forested period at the Two Creeks site from *ca*. 14,000 to 13,000 cal BP based on a compilation of wood radiocarbon dates, but they also inferred that ice-free conditions at the site would have commenced 1000–1500 years earlier. Additionally, a study of gastropod species and radiocarbon ages at the Two Creeks type locality by Rech *et al*. (2012) found evidence for the ice-free period with a taiga/tundra biome beginning even earlier, *ca*. 14,500 cal BP, which matches the starting point of our chronology. Our full 1408-year tree-ring width chronology suggests an extended ice-free period and the presence of pre-14,000 cal BP forest in the area. Independent support for the presence of such old wood is also indicated in the work of Suess (1979) who employed improved radiocarbon methods of the time to substantially reduce dating errors on Two Creeks wood relative to the earliest ages measured in the 1950s–1960s. He determined an age on some wood that was much older than the ages typical of wood from the forest bed of *ca*. 11,800 ^{14}C years (post-14,000 cal BP). This prompted his revised interpretation of the stratigraphy to show older logs in the lacustrine sediments below the forest bed (Suess 1979).

Our tree-ring assemblage includes wood collected at the classic Two Creeks forest bed in the 1950s through 1980s as well as our more recent wood collection after 2000, and from construction projects near Green Bay, WI, and vicinity (see Table 1 and the Sites section). The tree-ring chronologies suggest that there must have been multiple events of wood deposition over a multicentury time interval. Burial and preservation of wood was a consequence of post-Two Creekan ice advance, which impounded proglacial lakes in the Green Bay and Lake Michigan lowlands. As a result, wood is contained in glacial lake and wetland sediments (Garry *et al*. 1990), such as at the Jorgensen Farm and Paris Farm sites, in addition to preservation in overlying glacial till deposited when the ice sheet overran the sites.

The tree rings should contain signals of the Bølling-Allerød environmental variability. Because the conifer trees originated proximal to the edge of the continental ice sheet, the annual tree-ring variance most likely represents environments similar to the northern taiga and tundra of the modern boreal forests, which is supported by study of Morgan and Morgan (1979) finding fossil Coleoptera in the Two Creeks forest bed typical of a boreal forest environment. Growth of conifers at the northern tree limit for modern climates is usually dominated by temperature (*e.g.* MacDonald *et al*. 1998; Briffa *et al*. 2002; D'Arrigo *et al*. 2009). However, we do not know if other climate parameters might have increased importance to growth when the ice sheet was in close proximity.

Although this is the first Bølling-Allerød tree-ring chronology from N. America, Friedrich *et al*. (2001) developed a floating millennium-length tree-ring chronology in the Bølling-Allerød from ca. 14,300 to 13,300 cal BP using European pines.

Friedrich *et al.* (2001) interpret a pronounced depression in ring width at *ca.* 14,100 cal BP as the growth response to the cold Older Dryas climate. Another period of very small growth rings near 13,300 cal BP in the European record coincides with one of the gaps in our record, suggesting perhaps hemispheric cold conditions contributed to a paucity of trees in Wisconsin killed and transported to the lakeshore around that time. Interestingly, our other gap at 14,000 cal BP is close to a secondary ring-width minimum at 13,900 cal BP in the European record also pointing perhaps to hemispheric cold conditions (Figure 4).

Whereas the floating European Bølling-Allerød chronology was constructed solely with pine trees, the N. American chronology is dominated by spruce, with larch only in the youngest age cluster. Probably the wood collections include both white spruce (*Picea glauca*) and black spruce (*Picea mariana*) as represented in pollen records. Cones are diagnostic for spruce species, and both black spruce cones (Wilson 1936) and white spruce cones (Black 1970) have been reported at the Two Creeks type locality. Black spruce, like larch, is more likely associated with wetter lowland environments, but given the latitude and proximity to the ice sheet, all the species must have been strongly influenced by temperature, which has facilitated the crossdating among them.

CONCLUSIONS

A 1408-year annual tree-ring record was built from 135 specimens of well-preserved subfossil spruce and tamarack trees in eastern Wisconsin, US, and spans almost the full length of the Bølling-Allerød Interstadial from *ca.* 14,500 to 13,100 cal BP. This is the first millennium-length record of conifer tree rings in North America at the transition from the Late Pleistocene to the Holocene. The conifer trees were buried in various glacial, lake, and bog deposits, the preservation of which was aided by glacial front re-advances during cooling excursions within the Bølling-Allerød such as the Older Dryas. The record includes the subfossil trees of the Two Creeks type locality from a shoreline cliff eroded over many years, which at this site alone appears to have been forested from *ca.* 14,300 to 13,500 cal BP. The possible small gaps between clusters could represent periods of climate disturbance influencing stand dynamics and tree coverage on the periglacial landscape.

The abundance of preserved wood affirms the potential to extend this record forward to the Younger Dryas event and to increase the sample depth in order to bridge with confidence two apparent short gaps that remain in the record at *ca.* 14,000 and 13,300 cal BP. Because the trees grew at the northern most limit of Late Pleistocene boreal forests, it is very likely that the strong common signal estimated in the ring-width variance is associated with temperature fluctuations.

This study has provided a long Bølling-Allerød tree-ring chronology from the Great Lakes region of the North American mid-continent suitable for further paleoclimatic and environmental research. Similar deposits scattered throughout the study region may ultimately conserve a source of wood for building the first long and robust Late Pleistocene record.

Finally, our findings may also have relevance to improved understanding of the glacial history in North America and related lake-level history of ancestral Lake Michigan. Specifically, Two Creeks-age sites inundated by rising lake levels contribute to modeling of isostatic rebound and the timing of the Calumet Stage of glacial Lake Chicago (Clark *et al.* 2012; Curry *et al.* 2014).

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