Insights into Late Pleistocene–Early Holocene Paleoecology from Fossil Wood around the Great Lakes Region

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Introduction and background

Early publications about midwestern geology reported the finding of wood in glacial deposits (for example, Goldthwait, 1907; Alden, 1918). Goldthwait (1907) noted preserved wood along the shoreline on the west side of Lake Michigan, including the Two Creeks forest bed, which was overrun by the final advance of the Laurentide Ice Sheet. Wood is found around the Great Lakes in many geological circumstances associated with various modes of preservation, but the quality of the wood is variable from site to site. The deglaciation of the Great Lakes region was marked by rapid colonization of forests on the newly emergent terrestrial landscapes. Preserved remains of such forests provide tree rings for high-resolution climate-related analysis. For example, short-lived glacial readvances inundated some sites with water and sediment, resulting in burial and nearly ideal preservation of forest trees in original growth positions. Such was the case with trunks and branches preserved at the classic Two Creeks site in eastern Wisconsin. Wood as logs or in situ stumps has been preserved in submerged conditions (fig. 1) and also associated with eolian sands, alluvial deposits (fig. 2), lacustrine sediments, and bogs.

We have investigated wood at a number of sites around the Great Lakes (fig. 3; table 1) in an effort to better understand high-resolution environmental variability during the period from about

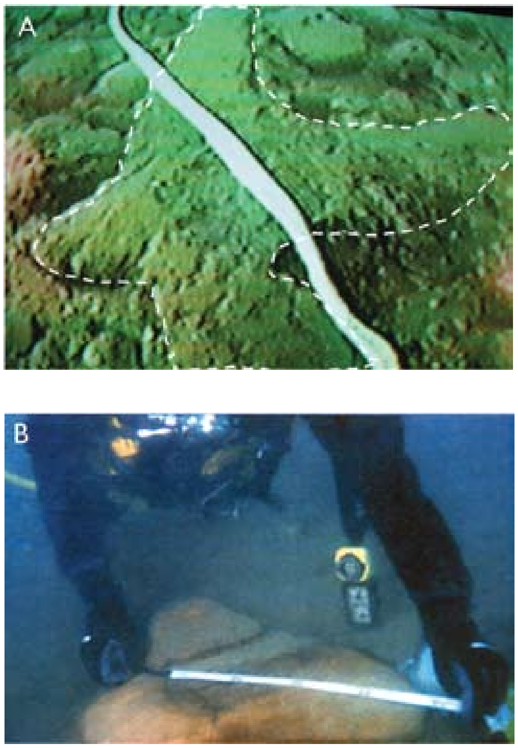

Figure 1. Stumps in submerged forests in Lake Michigan near Jacksonport in Door County, Wisconsin, at depth of approximately 12 m (A; dashed lines indicate outline of roots), and in Lake Huron near Sanilac County, Michigan, in approximately 12.5 m of water (B). (Photograph A by F. Pranschke; photograph B by L. Clyburn.)

Figure 2. Spruce stump with roots in Gribben Basin site, Michigan; the sand and gravel outwash was associated with a brief advance of the Laurentide Ice Sheet in Lake Superior. (Photograph by P.E. Martin.)

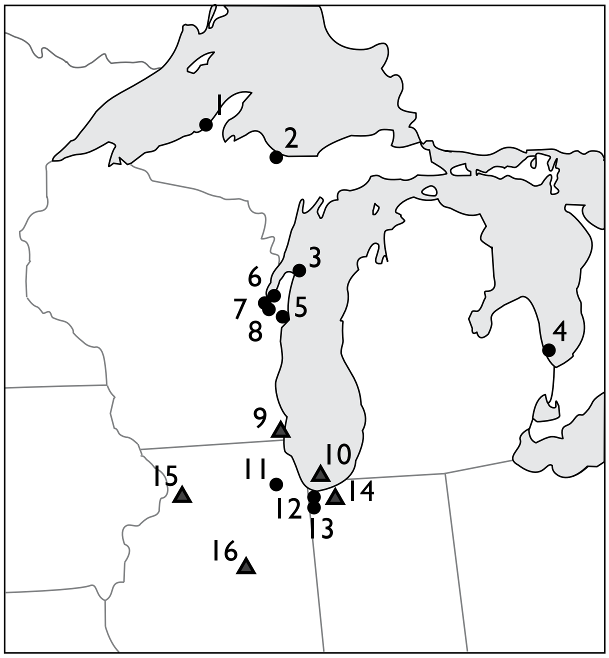

Figure 3. Location of recent and ongoing investigations involving wood between approximately 14,000 and 4,000 cal yr BP. Circles indicate conifers and triangles indicate hardwoods (angiosperms). 1=Elm River, 2=Gribben Basin, 3=Jacksonport, 4=Sanilac, 5=Two Creeks, 6= Green Bay–GB, 7=Green Bay–AH, 8=New Denmark, 9=Southport, 10=Olson, 11=Brewster, 12=Gary Sandpit, 13=Liverpool East, 14=Brown's Sandpit, 15=Markman, 16=Lincoln Quarry.

Table 1. Selected sites with ancient wood, in order of increasing age. Number next to site name refers to site in figure 3. *Carya*=hickory; *Gleditsia*=honeylocust; *Fraxinus*=ash; *Larix*=larch; *Morus*=mulberry; *Picea*=spruce; *Quercus*=oak; *Thuja*=white cedar; *Ulmus*=elm.

Site	Species	General radiocarbon age (^{14}C yr BP)	Approximate calibrated age (cal yr BP)	Information and dating source
12 Gary Sandpit	*Pinus*	3,100–4,000	3,300–4,500	Leavitt and others (2006)
1 Elm River	*Larix*	5,500–5,800	6,200–6,700	unpublished dates (S. Shetron; Panyushkina and Leavitt)
3 Jacksonport	*Thuja/Picea*	6,500	7,300–7,500	Pranschke and Shabica (1993); Leavitt and others (2006)
4 Sanilac	*Thuja*	6,400–7,100	7,300–8,000	Hunter and others (2006); Leavitt and others (2006)
9 Southport	*Quercus/Carya/ Fraxinus*	4,800–7,600	5,500–8,400	Sander (1969); Schneider and others (1977); Leavitt (1989)
10 Olson	*Quercus/Fraxinus*	8,100–8,400	9,000–9,500	Chrzastowski and others (1991); Pranschke and Shabica (1993)
15 Markman	*Ulmus*	9,000	10,000–10,200	Kim (1982); unpublished dates (Panyushkina and Leavitt)
11 Brewster	*Picea/Larix*	9,200–10,900	10,300–12,900	Curry and others (2006)
2 Gribben Basin	*Picea*	9,000–10.300	10,900–12,300	Lowell and others (1999); Pregitzer and others (2000); Leavitt and others (2006)
14 Brown's Sandpit	*Picea*	10,400–11,800	12,100–13,800	Cole (1987)
13 Liverpool East	*Picea*	9,920–10,420	11,200–12,600	Schneider and Hansel(1990); Morgan and others (1991); Leavitt and others (2006); Panyushkina and others (2005)
5 Two Creeks	*Picea*	11,600–12,000	13,300–13,900	Goldthwait (1907); Wilson (1932, 1936); Thwaites and Bertrand (1957); Broecker and Farrand (1963); Black (1970); Leavitt and Kalin (1992); Kaiser (1994)
8 New Denmark	*Picea*	11,600	13,300–13,500	Moran and others (1988); Leavitt and others (2006)
7 Green Bay–AH	*Picea*	11,100–11,300	12,900–13,200	Leavitt and others (2006)
6 Green Bay–GB	*Picea*	11,900	13,700–13,800	Schweger (1969); Thwaites (1958); Leavitt and others (2006)
16 Lincoln Quarry	*Fraxinus/Morus/ Gleditsia/Quercus*	8,500–14,100	9,500–17,000	Panyushkina and others (2004)

Figure 4. Black spruce *(Picea mariana)* cones found by I.P. Panyushkina at the Liverpool East site. (Photograph by S.W. Leavitt.)

14,000 to 4,000 years ago. Through the generous contribution of wood and site information from others, together with new collections at previously identified sites and recently discovered sites, we have amassed a collection of almost 600 wood specimens from more than 20 sites.

Generally, plant macrofossils such as cones and wood can be important resources for interpreting past environments. If identifiable from the macrofossils, tree species can sometimes be diagnostic of climate and environmental conditions (Thompson and others, 1999). For example, the black spruce (*Picea mariana*) cones (fig. 4) discovered at the Liverpool East site (ca. 10,000 ^{14}C yr BP) in northern Indiana are from a species associated with moist lowland conditions (Panyushkina and others, 2005). The white cedar (*Thuja*) and hemlock (*Tsuga*) dominated wood assemblage with coexisting pine (*Pinus*), spruce (*Picea*), and ash (*Fraxinus*) found in the submerged Sanilac site in Lake Huron (approximately 7,000 ^{14}C yr BP) indicates a community classification of "rich conifer swamp," also known as cedar swamp (Hunter and others, 2006).

The tree rings in wood samples can be particularly important in regard to what their ring size and pattern of growth indicate. For example, individual small rings in a sequence can denote a harsh growing environment that might have resulted from cold conditions at the end of the Pleistocene, and the sequence of changes in ring size during a tree's lifetime can indicate evidence of climate or competition effects. At the Two Creeks site, early observations of ring-size changes suggested suppression of growth in the final decades (for example, Wilson, 1932; Kaiser, 1994), which would be consistent with rising water levels as the readvance of the Lake Michigan Lobe of the Laurentide Ice Sheet blocked northern outlets of meltwater discharge.

We have examined the tree rings of a number of sites to establish tree-ring width "chronologies." We based these chronologies on cross-dating (correlating) the patterns of ring width among samples to establish the age relationship of rings. The chronologies of the late Pleistocene–early Holocene sites in the Great Lakes area are considered "floating" because they cannot be connected to modern tree-ring chronologies and are therefore not absolutely dated. In Europe, however, an absolute chronology from oak tree rings has been built back 10,000 years from modern living trees, historical wood from buildings and structures, and wood preserved in geologic deposits (Friedrich and others, 2004). The European chronology has been extended back to the late Younger Dryas (approximately 11,600 years ago) by matching with a floating pine chronology (Becker and Kromer, 1986). The Midwest floating chronologies we derived in the age range of approximately 10,000 to 14,000 years ago are depicted in figure 5. Although floating, it is possible to extract useful environmental information from the rings by means of the ring-width size and variability mentioned above, "event" chronologies based on micro-anatomical features (frost rings, reaction wood, traumatic resin ducts, etc.), isotopic composition, and spectral analysis of ring-width and isotope series.

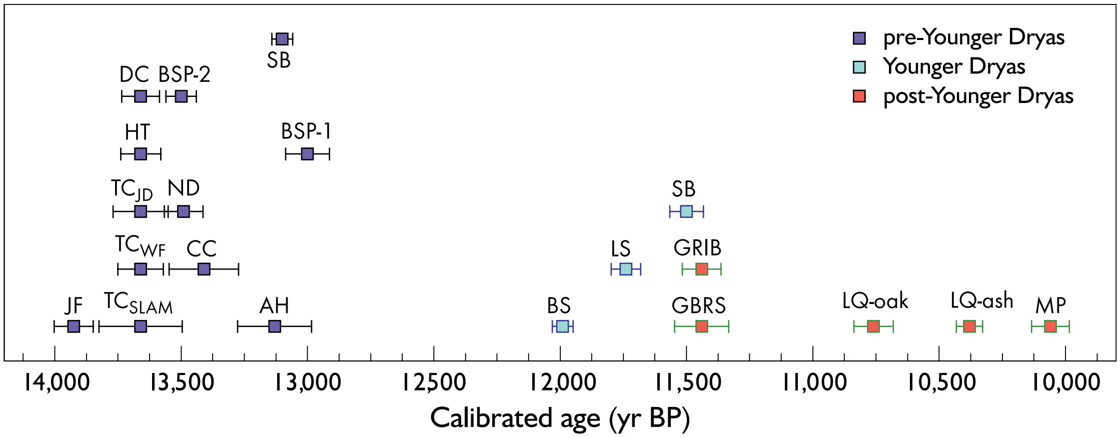

Figure 5. Distribution of the tree-ring chronologies over a 4,000-year interval of the Pleistocene-Holocene transition from Great Lakes sites (Panyushkina and Leavitt, 2006). Tree-ring width chronologies (horizontal bars) are plotted at midpoint of the respective calibrated radiocarbon age. The tree-ring width chronology length is represented by the length of the horizontal bars. The letters designate sites and collections; for example, "TC" represents Two Creeks type locality collections of different researchers (WF=W. Ferguson; JD=J. Dean; SLAM=S. Leavitt and A. McCord), "JF"=Jorgensen Farm, "CC"=Calumet County, "AH"=Green Bay-Amerihost, "ND"=New Denmark, "HT"=heating tunnel (UW-Green Bay), "DC"=Door County, "SB"=Schneider Farm, "BSP"=Brown's Sand Pit, "BS"=Brewster Creek, "LS"=Liverpool East, "GRIB" and "GBRS"=Gribben Basin, "LQ"=Lincoln Quarry, "MP"=Markman Peat. The Liverpool East site may actually plot closer to 12,000 cal yr BP on the basis of radiocarbon "wiggle-matching" of ring sequences to the master radiocarbon calibration curve (Leavitt and others, in press).

Example: sites of Two Creeks age

Four of the sites in figure 3 (and table 1) are considered to be approximately Two Creeks in age, and represent a small number of discoveries of Two Creeks equivalent wood reported around Wisconsin (four of which appear in figure 6, designated "Two Creeks," "Green Bay–AH", "Green Bay–GB", and "New Denmark"). Some of the reported finds of Two Creeks age material in the region are just single pieces of wood, even "twigs," rather than the assemblages of log samples that would be much more useful for dendrochronological work. However, we found that a lone log discovered in Calumet County, Wisconsin, had 278 rings, the most reported for any sample of Two Creeks age.

The length of the chronology from the Two Creeks type locality is 329 years, based on contributions from 52 trees, and aided greatly by the discovery of a single tree with 233 rings (fig. 7), just one ring short of the log reported by Kaiser (1994) and used in his initial chronology of 252 years developed from only wood in contact with the buried soil. The wood from these sites appears to be spruce, which Kaiser (1994) considered to be black spruce. However, there may well have been white spruce (*Picea glauca*) on upland sites and black spruce on lowland sites—Black (1970) suggested that white spruce in the area was generally more abundant here than black spruce.

Nobel Prize recipient Willard Libby (1955) was the first to date wood of the Two Creeks type locality to 10,700 to 12,200 ^{14}C yr BP. Broecker and Farrand (1963), Black and Rubin (1967–68), Suess (1979), Leavitt and Kalin (1992), and Kaiser (1994) have subsequently dated several pieces of wood from the site. The fairly consistent results of Broecker and Farrand (1963), Leavitt and Kalin (1992), and Kaiser (1994) have substantially refined the age estimate

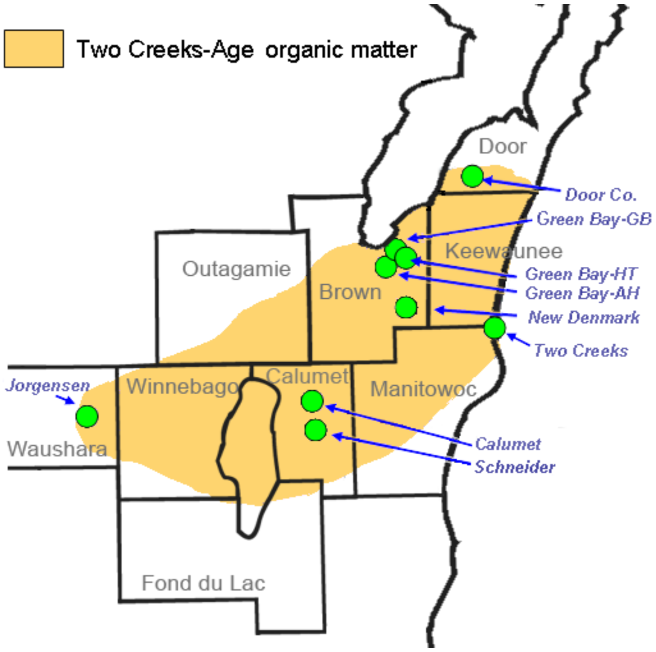

Figure 6. Locations where Two Creeks age-equivalent wood has been found (modified from Black, 1970).

to an average of approximately 11,800 to 11,850 ^{14}C yr BP. The youngest dates of Kaiser (1994) on outside rings tend to fall close to 11,600 ^{14}C yr BP, concordant with what might be expected if the forest bed represented a lifespan of approximately 300 calendar years. Leavitt and others (in press) estimated an outer age in the tree-ring series of approximately 11,600 ^{14}C yr BP, which is equivalent to approximately 13,530 cal yr BP, on the basis of radiocarbon "wiggle"-matching.

Wood being eroded out of the type locality bluff along Lake Michigan has been observed as stumps rooted in the forest bed (fig. 8) and as logs, primarily in the lacustrine sediments immediately above the forest bed, but also in the red till above the lacustrine sediments (Goldthwait, 1907; Wilson, 1932; Black, 1970), with the logs in the till having been transported the farthest. Wilson (1932) suggested that the trees in the lacustrine

Figure 7. Large log (possibly part of a tipped stump) containing 233 rings discovered at the Two Creeks type locality in 2003. (Photograph by I.P. Panyushkina.)

Figure 8. Stump tilting toward southwest at Two Creeks type locality with roots in the soil horizon and trunk extending up through gray lacustrine sediments. The upper end of trunk is truncated as if sheared off by the advance of the ice sheet past this position. (Photograph by S.W. Leavitt.)

sediments were growing closest to the site and showed a decade or two of growth suppression of the tree rings in response to rising water levels; those in the till did not show the growth suppression, perhaps because they were from upland localities. In most cases, the stratigraphic position of the wood in our collections is unknown, usually because the wood has been eroded out of the bluff. Thus, the 329-year provisional tree-ring chronology undoubtedly contains wood that is likely local as well as wood that has been transported some significant (but unknown) distance north. However, the end of the chronology should represent those trees that had survived the longest (probably local trees) before their ultimate demise from rising water and eventual overriding by the Lake Michigan Lobe.

The Two Creeks ring-width series was standardized into a ring-index series, which removes non-climatic effects, such as long-term growth trends, and produces a mean series index of 1.0 (Fritts, 1976). The tree-ring index variability represents changes of environmental conditions for the period of 329 years at this locality (fig. 9). Only a few positive periods (>1.0) were favorable to tree-ring growth. Pronounced and abrupt negative growth episodes (<1.0) are more frequent in this record. On the basis of the relationship between modern spruce tree rings and mountain glacier mass balance from the Coastal Mountains in British Columbia (Larocque and Smith, 2005), the Two Creeks tree-ring record might be related to dynamics of the Lake Michigan Lobe. The positive tree-ring growth periods could be associated with warmer summer conditions and degradation of the ice sheet. The negative periods of tree rings more likely represent advances of the ice sheet.

We also aligned tree-ring width records of spruce from eight sites of suspected Two Creeks age to the end of growth at the Two Creeks type locality and correlated pointer intervals (distinct sequences of low or high tree-ring values identified visually). It seems that the unique signatures of tree-ring width variability correspond well among these sites (fig. 10), suggesting that the trees responded to the same environmental impacts across the region. Furthermore, wood from some locations showed high spruce growth (mean 0.66–0.46 mm for New Denmark and Green Bay-GB and AH) and higher variance of radial growth (0.27–0.25) in relation to some of the other sites (mean 0.36–0.40 mm and standard deviation 0.22–0.14 for Two Creeks, Green Bay–HT, Door County, and Calumet). There are seven strong and synchronized events of negative impact on tree growth more than 150 years before the Two Creeks trees were buried: The trees

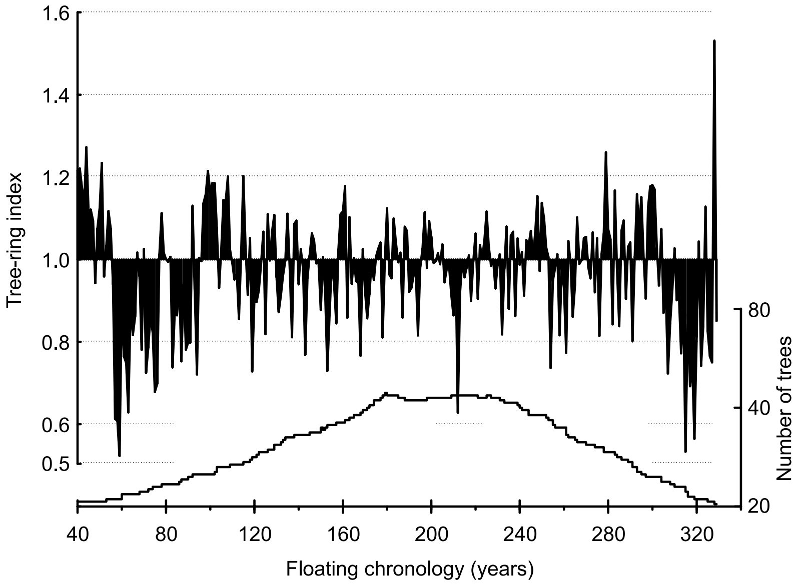

Figure 9. Tree-ring width index chronology of the Two Creek site (upper curve) and number of trees contributing to chronology (lower curve).

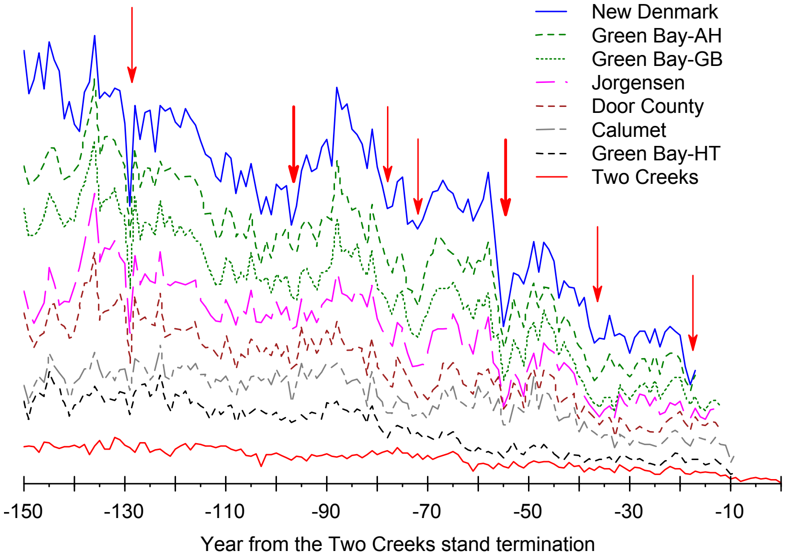

Figure 10. "Stacked plots" of averaged tree-ring width chronologies for locations of Two Creeks age material. Tree-ring width means increase from bottom to top. Caution: The true means and variability are not equally scaled among the sites, so they cannot be compared. The value of these plots is to highlight common response of trees to events and absolute differences in stand termination dates. Red arrows indiate pointer years.

responded strongly to negative impact at 129, 97, 78–77, 72, 55, 37–36 and 19 years before the dieback. These one- and two-year events could be an impact of meltwater and outwash, and there is evidence of traumatic resin ducts in some of the trees following these negative events.

Wilson (1932, 1936) suggested trees found in the red till at the type locality had larger rings than those in or near the forest bed horizon, and therefore represent trees being transported from sites with more favorable growth conditions. We found that average tree-ring widths at the type locality (including logs from all horizons) were actually narrower than those of all the other sites. Furthermore, Wilson (1932, 1936) suggested that some individual small rings of the wood from nearest the forest bed corresponded to wide rings in the wood from the red till above, suggesting that excessive moisture reduced growth close to the shoreline, but enhanced growth in the trees on higher ground from which the wood in the red till was presumably transported. However, our results (fig. 10) suggested occurrences of narrow (and wide) rings are consistent across a large area and over a range of 80 m or more of elevation, so a more universal environmental influence would be required to explain the narrow rings. Perhaps katabatic winds might be a better explanation than meltwater and outwash for this widespread impact.

Termination of all stands occurred within a 17-year period, according to the tree-ring records (fig. 10). It seems the spruce survived longer at the Two Creeks locality in comparison with other sites. However, we do not know how well the breadth of our collection captures true stand ages and termination dates.

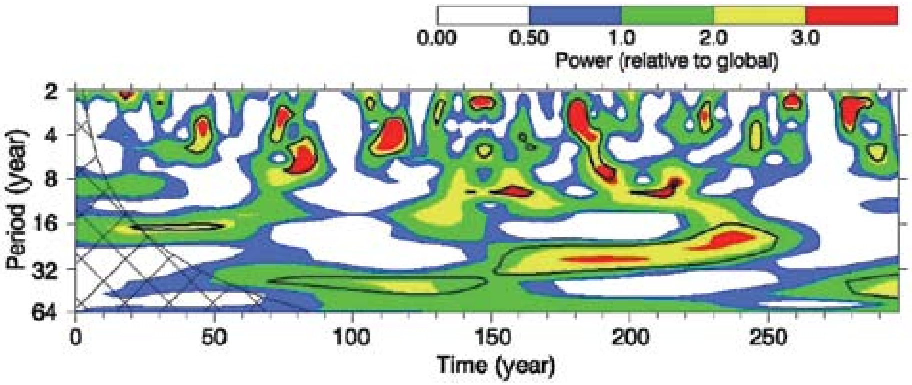

Figure 11. The wavelet power spectra for tree rings from the Two Creeks type locality with the first 30 years of record cut off (Panyushkina and Leavitt, 2006). The Morlet wavelet function in Fourier space was applied, and the power has been normalized by the global wavelet spectrum that measures the deviation from the mean spectrum. The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 90 percent significance level, using a red-noise (autoregressive lag 1) background spectrum.

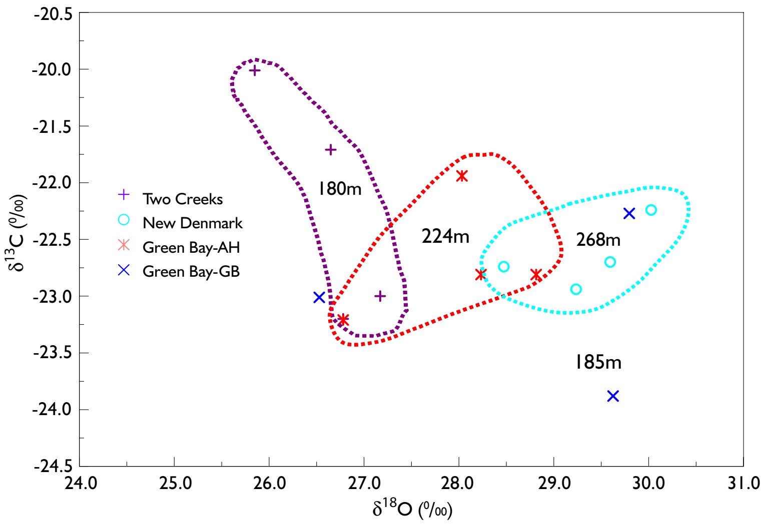

Figure 12. Clusters of points for the Two Creeks, Green Bay–AH, and New Denmark sites in $\delta^{13}C$–$\delta^{18}O$ space. Site elevations above sea level are indicated. The Green Bay–GB site seems to spread across and outside the fields of the other site values. (Modified from Leavitt and others, 2006.)

We analyzed the spectral characteristics of this series (fig. 11) to determine how they compared to modern large-scale climate drivers, such as the ENSO phenomenon that exhibits periodicity of 2.8 to 7.6 years. We detected this periodicity in the index series, at least intermittently, and also observed another strong period of 20 to 30 years. Interestingly, the Two Creeks record showed a 100-year period between years 150 and 250 with high power of the 20 to 30 year periodicity that may be forced by solar magnetic activity (centered at 25–30 years in our case), which weakened toward the end of the record. It seems to correspond to other lines of evidence on the climatic nature of variability seen in the tree-ring records of the Two Creeks age.

The bulk stable isotope composition ($\delta^{13}C$, $\delta^{18}O$, and $\delta^{2}H$) of wood from four of the Two Creeks age sites was also analyzed for several samples per site (Leavitt and others, 2006). A plot of $\delta^{13}C$ and $\delta^{18}O$ indicates that three sites can be distinguished (Two Creeks, New Denmark, and Green Bay–AH) with respect to the fields in which their points lie (fig. 12). Although the $\delta^{13}C$ values seem to largely overlap, the three sites seem to cluster according to modern elevation differences. However, the pattern is the opposite of what would be expected if orographic lifting were decreasing the $\delta^{18}O$ value of water vapor and precipitation eventually incorporated into the tree rings. More likely, temperature is contributing to this phenomenon, related to greater daytime temperatures farther inland (higher elevations) and away from lake cooling during the growing season (Leavitt and others, 2006). The Green Bay–GB site does not follow this pattern, but it was collected from sediments that show evidence of deformation (Schweger, 1969), and therefore the provenience is less certain. This illustrates the great value of having wood from multiple sites of the same age to examine spatial as well as temporal aspects of regional environmental variability.

Conclusions

Wood has been found in geological deposits at a number of sites in the Midwest, and although it is extremely desirable for radiocarbon dating, it has been largely underutilized with respect to environmental reconstructions. In part, this may be a consequence of the uneven quality of wood preservation dependent on conditions of burial, subsurface processes during burial (including hydrology, microbial activity, oxidation potential), and post-depositional effects. Ring-width measurements and chronology development, tabulation of event chronologies, stable isotope analysis, and specialized methods of data and time-series analysis offer great promise for extracting useful and perhaps diagnostic environmental information from this resource.

We have systematically applied these methods to wood from some long-known deposits as well as others that were very recently discovered. Fortunate geological circumstances of wood preservation and chance discovery have resulted in a wide age range of chronologies, but the typical chronology length of approximately 100 to 200 years means that it will be difficult to develop a continuous absolute chronology dating back 10,000+ years, similar to that being developed in Europe. However, good professional contacts will be helpful in continuing acquisition of suitable samples and filling in some of the gaps, and radiocarbon wiggle-matching may resolve the absolute age within a decade or two in the absence of a continuous absolute chronology. The acquisition of contemporaneous wood from widely separated sites offers the opportunity to make further inferences about regional characteristics of high-resolution climate variability.

Acknowledgments

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References

Alden, W.C., 1918, Quaternary geology of southeastern Wisconsin: U.S. Geological Survey Professional Paper 106, 356 p.

Becker, B., and Kromer, B., 1986. Extension of the Holocene dendrochronology by the Preboreal pine series, 8800 to 10,100 BP: *Radiocarbon* v. 28, no. 2B, p. 961–967.

Black, R.F., 1970, Glacial geology of the Two Creeks forest bed, Valderan type locality, and northern Kettle Moraine State Forest: Wisconsin Geological and Natural History Survey Information Circular 13, p. 21–30.

Black, R.F., and Rubin, M., 1967–68, Radiocarbon dates of Wisconsin: *Transactions of the Wisconsin Academy of Sciences, Arts and Letters*, v. LVI, p. 99–115.

Broecker, W.S., and Farrand, W.R., 1963, Radiocarbon age of the Two Creeks forest bed, Wisconsin: *Geological Society of America Bulletin,* v. 74, p. 795–802.

Chrzastowski, M.J., Pranschke, F.A., and Shabica, C.W., 1991, Discovery and preliminary investigations of the remains of an early Holocene forest on the floor of southern Lake Michigan: *Journal of Great Lakes Research,* v. 17, no. 4, p. 543–552.

Cole, K.L., 1987. Late Wisconsin spruce forest on the south end of Lake Michigan: International Union for Quaternary Research (INQUA), Programme and Abstracts for the XIIth International Congress, Ottawa, p. 146.

Curry, B.B., Grimm, E.C., Slate, J.E., Hansen, B.C., and Konen, M.E., 2006, Paleohydrology, paleovegetation, and sedimentology of the near-surface silt–marl–peat succession at the Brewster Creek site, a typical Chicagoland wetland: Program and Abstracts of the XIX Biennial Meeting of the American Quaternary Association, Bozeman, Montana, 14–22 August 2006, p. 83–84.

Friedrich, M., Remmele, S., Kromer, B., Hofmann, J., Spurk, M., Kaiser, K.F., Orcel, C., and Küppers, M., 2004, The 12,460-year Hohenheim oak and pine tree-ring chronology from central Europe—A unique annual record for radiocarbon calibration and paleoenvironment reconstructions: *Radiocarbon,* v. 46, no. 3, p. 1161–1187.

Fritts, H.C., 1976, *Tree Rings and Climate:* Academic Press, London.

Goldthwait, J.S., 1907, The abandoned shorelines of eastern Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 17, 134 p.

Hunter, R.D., Panyushkina, I.P., Leavitt, S.W., Wiedenhoeft, A.C., and Zawiskie, J., 2006, A multiproxy environmental investigation of Holocene wood from a submerged conifer forest in Lake Huron, USA: *Quaternary Research,* v. 66, p. 67–77.

Kaiser, K.F., 1994, Two Creeks Interstade dated through dendrochronology and AMS: *Quaternary Research,* v. 42, p. 288–298.

Kim, H.K., 1982, Late-glacial and postglacial pollen studies from the Zuehl Farm site, north-central Iowa and the Cattail Channel bog, northwestern Illinois: M.S. Thesis, University of Iowa.

Larocque, S.J., and Smith, D.J., 2005, "Little Ice Age" proxy glacier mass balance records reconstructed from tree rings in the Mt. Waddington area, British Columbia Coast Mountains, Canada: *Holocene,* v. 15, no. 5, p. 748–757.

Leavitt, S.W., 1989, Tree-ring characteristics of wood samples from the Southport area buried forest, Kenosha, Wisconsin: Wisconsin Academy of Sciences, Arts and Letters Conference Abstracts, April 29, 1989.

Leavitt, S.W., and Kalin, R.M., 1992, A new tree-ring width, $\delta^{13}C$ and ^{14}C investigation of the Two Creeks site: *Radiocarbon,* v. 34, p. 792–797.

Leavitt, S.W., Panyushkina, I.P., Lange, T., Cheng, L., Schneider, A.F., and Hughes, J., in press, Radiocarbon "wiggles" in Great Lakes wood ca. 10,000 to 12,000 BP: *Radiocarbon.*

Leavitt, S.W., Panyushkina, I.P., Lange, T., Wiedenhoeft, A., Cheng, L., Hunter, R.D., Hughes, J., Pranschke, F., Schneider, A.F., Moran, J., and Stieglitz, R., 2006, Climate in the Great Lakes region between 14,000 and 4,000 years ago from isotopic composition of conifer wood: *Radiocarbon,* v. 48, p. 205–217.

Libby, W.F., 1955, *Radiocarbon Dating,* 2nd edition: University of Chicago Press, 175 p.

Lowell, T.V., Larson, G.J., Hughes, J.D., and Denton, G.H., 1999, Age verification of the Lake Gribben forest bed and the Younger Dryas advance of the Laurentide ice sheet: *Canadian Journal of Earth Science,* v. 36, p. 383–393.

Moran, J.M., Stieglitz, R.D., and Quigley, D.P., 1988, Glacial geology, road construction in northeast Wisconsin reveals clues to Earth's natural history: *Earth Science*, winter, p. 16–18.

Morgan, A.V., Pilny, J.J., and Schneider, A.F., 1991, Coleoptera fauna and paleoenvironment of the Liverpool East site, northwestern Indiana: Geological Society of America Abstracts with Programs, v. 23, no. 3, p. 50.

Panyushkina, I.P., and Leavitt, S.W., 2006, Late glacial–early Holocene climate variability in the Great Lakes region from tree rings: AMQUA Program and Abstracts, 19th Biennial Meeting, Bozeman, Montana, August 2006, p. 137.

Panyushkina, I.P., Leavitt, S.W., Wiedenhoeft, A., Noggle, S., Curry, B., and Grimm, E., 2004, Tree-ring records of near-Younger Dryas time in central North America—Preliminary results from the Lincoln Quarry site, central Illinois, USA: *Radiocarbon,* v. 46, p. 933–941.

Panyushkina, I.P., Leavitt, S.W., Lange, T., Schneider, A.F., 2005, Tree-ring investigation of an *in situ* Younger Dryas-Age spruce forest in the Great Lakes Region of N. America: *Eos Transactions, AGU,*

v. 86, no. 52, Fall Meeting Supplement, Abstract PP13A-1484.

Pranschke, F., and Schabica, C.W., 1993, The remains of an 8200-year old forest on the floor of southern Lake Michigan: Final Report to the National Geographic Society, Grant #4748-92.

Pregitzer, K.S., Reed, D.D., Bornhorst, T.J., Foster, D.R., Mroz, G.D., McLachlin, J.S., Laks, P.E., Stokke, D.D., Martin, P.E., and Brown, S.E., 2000, A buried spruce forest provides evidence at the stand and landscape scale for the effects of environment on vegetation at the Pleistocene/Holocene boundary: *Journal of Ecology,* v. 88, p. 45–53.

Sander, P., 1969, Kenosha sand dunes: *Wisconsin Academy Review,* v. 16, no. 3, p. 2–6.

Schneider, A.F., and Hansel, A.K., 1990, Evidence for post-Two Creeks age of the type Calumet shoreline of glacial Lake Chicago: Geological Society of America Special Paper 251, p. 1–8.

Schneider, A.F., Sander, P., and Larsen, C.E., 1977, Late Quaternary buried forest bed in southeastern Wisconsin: Geological Society of America Abstracts with Programs, v. 11, p. 256.

Schweger, C.E., 1969, Pollen analysis of Iola bog and paleoecology of the Two Creeks forest bed, Wisconsin: *Ecology,* v. 50, p. 859–869.

Suess, H.E., 1979, Were the Allerød and Two Creeks Substages contemporaneous? *in* Berger, R., and Suess, H.E., eds., Radiocarbon dating: Proceedings of the Ninth International Radiocarbon Conference: University of California Press, p. 76–82.

Thompson, R.S., Anderson, K.H,. Bartlein, P.J., 1999, Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America: U.S. Geological Survey Professional Paper 1650A. Available online at http://pubs.usgs.gov/pp/p1650-a/.

Thwaites, F.T., 1958, The Green Bay forest bed locality: Wisconsin Geological and Natural History Survey Open-File Report 1958-1, 3 p.

Thwaites, F.T., and Bertrand, K., 1957, Pleistocene geology of the Door Peninsula, Wisconsin: *Geological Society of America Bulletin,* v. 68, p. 831–880.

Wilson, L.R., 1932, The Two Creeks forest bed, Manitowoc County, Wisconsin: *Transactions of the Wisconsin Academy of Science, Arts and Letters,* v. XXVII, p. 31–46.

Wilson, L.R., 1936, Further studies of the Two Creeks forest bed, Manitowoc County, Wisconsin: *Bulletin of the Torrey Botanical Club,* v. 63, no. 6, p. 317–325.