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# A multiproxy environmental investigation of Holocene wood from a submerged conifer forest in Lake Huron, USA

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## Abstract

Remains of a Holocene drowned forest in southern Lake Huron discovered in 12.5 m of water (164 m above sea level), 4.5 km east of Lexington, Michigan USA (Sanilac site), provided wood to investigate environment and lake history using several proxies. Macrofossil evidence indicates a forest comprised primarily of conifers equivalent to the modern "rich conifer swamp" community, despite generally low regional abundance of these species in pollen records. Ages range from 7095 ± 50 to 6420 ± 70 $^{14}$C yr BP, but the clustering of stump dates and the development of 2 floating tree-ring chronologies suggest a briefer forest interval of no more than c. 400 years. Dendrochronological analysis indicates an environment with high inter-annual climate variability. Stable-carbon isotope composition falls within the range of modern trees from this region, but the stable-oxygen composition is consistent with warmer conditions than today. Both our tree-ring and isotope data provide support for a warmer environment in this region, consistent with a mid-Holocene thermal maximum. This drowned forest also provides a dated elevation in the Nipissing transgression at about 6420 $^{14}$C yr BP (7350 cal yr BP) in the southern Lake Huron basin, a few hundred years before reopening of the St. Clair River drainage.


*Keywords:* Lake Stanley; Tree rings; Stable isotopes; Lake Huron; Holocene; Lake levels; *Thuja*

## Introduction

Important chapters in the natural history of the Great Lakes have been supplemented by wood preserved in a variety of geologic deposits and environments, including submerged settings. In the upper Great Lakes region several sites in Lake Michigan have already been reported with submerged stumps, such as the Olson site east of Chicago, IL, in about 25 m of water (Chrzastowski et al., 1991; Fig. 1 site 1), the Southport site exposed by lake erosion near shoreline level in Kenosha County, WI, (Sander, 1962; Schneider et al., 1979; Leavitt, 1989; Fig. 1 site 2), and at a depth of about 37 m in the Straits of Mackinac where Lake Michigan and Lake Huron are connected (Crane and Griffin, 1970, 1972; Fig. 1 site 3). In Lake Huron, wood remains have been located at Thompson's Harbor (Fig. 1 site 4), and in various parts of the Georgian Bay region (Fig. 1, sites 5 and 6) (Lewis and Anderson, 1989; Larsen, 1987; and citations therein). A site with stumps in growth position submerged in c. 12.5 m of water (elevation 163.5 m above sea level) in southwestern Lake Huron (approximately 43° 16.17′N, 82° 28.42′W; Fig. 1 site 9) was discovered in 1988 by SCUBA diver Timothy Juhl and associates about 4.5 km offshore, east of Lexington, Michigan. This find was later designated the Sanilac site, named after the Michigan County along the adjacent shoreline, and is the subject of this paper.

The Sanilac macrofossil evidence affords an exceptional opportunity to examine conditions during an isostatically and climatically dynamic time interval within the Holocene. Although the Lake Huron and Michigan basins were free of glaciers throughout the Holocene, lake levels were far from static. Periods of low water level favored establishment of

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Figure 1. Map of the Laurentian Great Lakes indicating the Sanilac forest (site 9) and other previously reported localities (described in text) with known radiocarbon dates in Lakes Michigan and Huron and in the St. Clair River delta.

forests such as preserved at the Sanilac site, and rising water facilitated their subsequent preservation. Notable among these periods in the early-to mid-Holocene is the Chippewa low-water phase in Lake Michigan and a contemporaneous Stanley low phase in Lake Huron when the lake levels were at their lowest, possibly over 100 m lower than the current level. The Chippewa is characterized by a very rapid asymmetric decline in water levels in the first 500 yr and a generally more gradual rise over the remainder of the period. Although the end of these lake phases overlaps with a warm climate event known as the Hypsithermal (a.k.a. Altithermal and mid-Holocene Climate Optimum and mid-Holocene thermal maximum), the cause of the low lake levels is attributed to isostatic crustal depression of the northern reaches of these lakes by the weight of the continental ice sheet and then isostatic rebound after the glacier retreat from the region (Hansel et al., 1985). Based on bathymetric charts, there were times during the Stanley and Chippewa low stands when more than 50% of the area currently covered by the lakes was above water level, with the broadest expanses of emergent land in the southern parts of lakes Michigan and Huron (Lewis et al., 1994; Holcombe et al., 1996). At the extreme low, the Mackinac Channel in the Straits of Mackinac connected Lake Chippewa to a 10–15 m lower lakes Stanley (Stanley, 1938; Hough, 1962; Holcombe et al., 1996). It was during this prolonged low-water phase that vegetation, including forests, was able to establish and flourish on the landscape approximately 8000 to 5000 $^{14}$C yr BP until flooded during the Nipissing transgression (Lewis and Anderson, 1989).

## Geologic setting

A prominent submerged escarpment of Devonian carbonate rock of the Dundee Limestone and Traverse Group separates a southern basin from the main Lake Huron basin. The Sanilac drowned forest site in the southern basin occurs on clay-rich till with a thin patchy irregular sand cover. The water-laid till was deposited roughly 13,000 yr ago when the ice melted out at the position of the Port Huron moraine (Fullerton, 1980). Most of the sand on the western shore of Lake Huron in Sanilac county occurs as near shore deposits winnowed from till in the eroding headland shoreline cliffs. Westerly winds that maintained during Lake Nipissing time created the conditions for large dune formation primarily on the eastern shores of the southern Lake Huron Basin. There is, however, evidence of polar anticyclonic easterly winds off the Laurentide ice sheet in late glacial time (11,000 yr ago) during the lifetime of Lake Algonquin that created dunes and spits in beach complexes inland from the present western lake shore (Krist and Schaetzl, 2001).

The objective of this study was to use analyses of age, species, tree-ring characteristics, and stable isotope composition to address how this site fits into current understanding of major lake-level fluctuations, how the forest assemblage at this site compares to modern forests at the site and in the region, and whether climate was different from that of the present.

## Methods

Exploratory fieldwork at the site was conducted in 1998–2000, with comprehensive fieldwork occurring in late summer 2001 facilitated by volunteer divers of the U.S. Naval Sea Cadet Corps, Great Lakes Division. Dive teams laid out a one hectare square grid of one hundred cells, each measuring 10 × 10 m. Within each cell, the wood remains were inventoried.

A suite of wood cross-sections from roots, stumps and logs was collected from the grid using handsaws. Twenty of the samples were slowly dried, cut into cross-sections and polished by sanding. Small wood fragments were sub-sampled for wood species identification. For radiocarbon dating, in the majority of cases whole available cross-sections were sub-sampled and ground to 20-mesh size. In some cases, however, a select interval of rings was separated. The holocellulose component was isolated for dating by extracting the ground wood with toluene–ethanol and ethanol in a soxhlet extraction apparatus, boiling in de-ionized water, and delignified with an HCl-acidified sodium chlorite solution at 70°C (see Leavitt and Danzer, 1993). At the University of Arizona conventional radiocarbon laboratory, the samples were converted to $CO_2$, reduced to benzene, and dated by liquid scintillation counting. The CALIB5 program (Reimer et al., 2004) was used to convert $^{14}C$ years before present ($^{14}C$ yr BP) to calibrated years before present (cal yr BP relative to A.D. 1950).

Wood identification (by A.C.W.) was performed at the USDA Forest Products Laboratory, Madison, WI, through examination of tangential, radial and transverse thin sections. Sections were hand cut from non-embedded stock, infiltrated with glycerine:alcohol at 70–100°C and examined microscopically using transmitted and polarized light. For tree-ring analysis, each cross-section was examined to determine degree of wood decomposition and disturbance of ring width patterns. Seven specimens out of the 20 were deemed suitable for ring-width measurements. We measured widths along several radii of each cross-section, avoiding radii with reaction wood and ring widths contorted by decay processes (or distortion of ring widths from drying). Tree-ring width series from two radii per sample were measured on a Henson measuring system (0.01 mm precision). Strength of matched (crossdated) tree-ring width series was estimated with Pearson correlation coefficients and by visual examination of overlapping plots in TSAP software (Rinn, 2003).

The stable-carbon isotope composition ($\delta^{13}C = (^{13}C_{sample}/^{13}C_{std} - 1) \times 1000)$) of holocellulose samples was measured via on-line pyrolysis on a Finnigan Delta-Plus isotope ratio mass spectrometer with respect to the international PDB standard (Coplen, 1996). The stable-oxygen isotope composition ($\delta^{18}O = (^{18}O_{sample}/^{18}O_{std} - 1) \times 1000)$) of holocellulose samples was likewise measured via on-line pyrolysis on a Finnigan Delta-Plus isotope ratio mass spectrometer with respect to the international V-SMOW standard (Coplen, 1996).

## Results and discussion

### *Field survey*

To our knowledge, this drowned forest is the largest reported aggregation of Holocene tree remains on the bottom of the modern Great Lakes. The lake bottom at the Sanilac site is relatively flat with only minor (30 cm or less) changes in elevation. Sediments were mostly sand mixed with light-colored clay, overlain with occasional scattered pebbles often characterized by current-generated undulations.

In areas where tree remains were visible, the wood was mostly broken up into pieces of a meter or less in length, rarely extending above the bottom sediments for more than 0.5 m. Exceptions tended to be logs that were occasionally found lying on the bottom. Figure 2A shows a spruce stump in situ with its outer surface loosely covered with filamentous algae and zebra mussels. The outer 1–2 cm of wood was soft and decomposing;

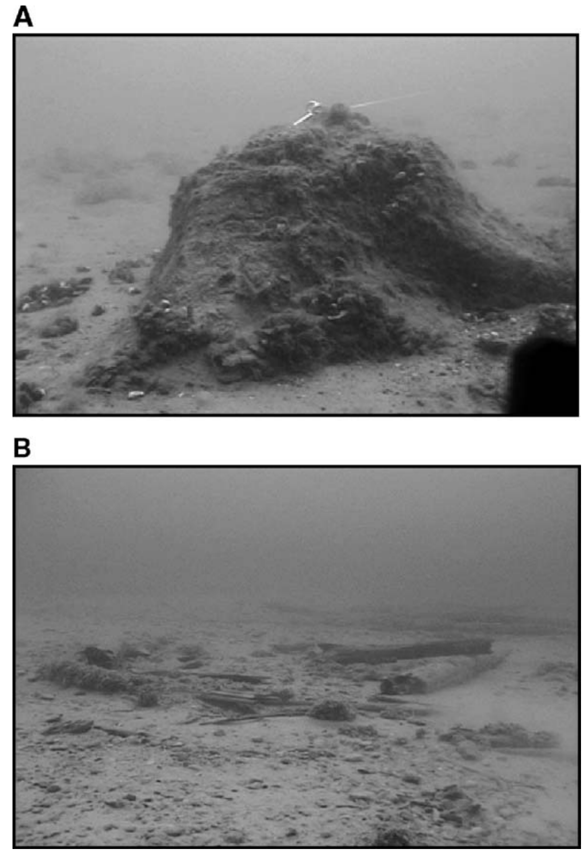


Figure 2. (A) Photo of a submerged spruce stump at the Sanilac site from which the cross-section of sample #1 was cut in July 1999. Approximate diameter of this stump at its base is 60 cm. (B) View across an area of dense forest remains located near the study grid. The larger logs to left of center are c. 3.7 m in length. Depth for both photos = 13 m. Photos by Luke Clyburn.

inner wood was far more durable. The overall impression is that patches of the forest have been exhumed by storm surge or other modern events and, once exposed, the wood has undergone accelerated decomposition.

In the 2001 field survey, a 1-ha grid was intensively sampled yielding about 500 visible pieces of wood including logs, branches, roots, and 10 stumps (Fig. 3). Other wood remains were observed near the grid including highly deteriorated stumps as large as 150 cm in diameter and relatively intact logs as large as 60 cm in diameter (Fig. 2B). Stumps were uncommon as were large and relatively intact logs. Unfortunately, the largest stumps were too degraded to sample for dendrochronological analysis.

The two samples collected during the 1999 field season, samples #1 and #2, were a stump and a log, respectively (Table 1). Samples #3–6 were collected in 2000, and all appeared to be stumps although only sample #6 had actual roots still attached. Samples #5 and #6 had a lobate trunk appearance, indicating the position of these cross sections was in the basal area of the hemlock trees. Highly decayed small samples (e.g., #3 and #4) were possibly either branches or small logs, but if they were oriented vertically in the sediment, as was #5, they were considered trunks. Samples #7–19 were located within the grid.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 8 | 0 | 0 | 0 | 1 | 7 | 0 | 0 | 1 | 8 |
| 0 | 0 | 0 | 0 | 16 | 42 * | 9 * | 15 * | 8 * | 2 |
| 0 | 0 | 0 | 0 | 13 | 41 | 17 * | 8 | 2 * | 2 |
| 0 | 0 | 0 | 0 | 7 | 25 | 20 | 6 | 0 | 0 |
| 0 | 0 | 0 | 0 | 10 | 21 | 47 * | 24 | 4 | 0 |
| 0 | 3 | 0 | 0 | 0 | 5 | 33 | 16 | 7 * | 0 |
| 2 | 0 | 0 | 0 | 8 | 9 | 3 | 11 | 6 | 0 |
| 0 | 0 | 0 | 2 | 7 * | 2 | 10 | 16 * | 6 | 0 |
| 0 | 0 | 0 | 0 | 6 | 2 | 6 | 4 | 6 | 0 |

Figure 3. Density of wood occurrence in each 10 × 10 m cell of the 1-ha grid at the Sanilac site. The number in each cell refers to quantity of discreet wood remains; * = stump. Cells were numbered sequentially from left to right with "1" in the northwest corner and "100" in the southeast corner (grid locations in Table 1).

We examined approximately 3 ha of the bottom, characterized as patchy wood debris separated by expanses of sandy clay bottom. We believe that the exposed wood extends over a larger area but the full extent of this exposure was not explored because of limitations of visibility and diver time/effort. Based on very limited core samples and extensive observations of roots and branches protruding from the sediment–water interface, there is undoubtedly a considerable volume of wood that is hidden from view beneath bottom sediments.

Attempts to penetrate the surface sediment layer using hand-driven and vibracore devices met with little success, due to the marked resistance of the sand/clay mix and by subsurface obstructions such as cobbles and wood debris. A 0.4-m core contained sand and clay similar to that seen at the surface. The impression from these cores and shallow excavation is that the original terrigenous soil at this site was, at some point, replaced by lacustrine sediments, at least up to 30 cm.

### *Sanilac species association*

Based on wood identification (Table 2), Sanilac was overwhelmingly a conifer forest dominated by *Thuja* (50%) and *Tsuga* (20%), with evidence of coexisting pine (*Pinus*) (10%), spruce (*Picea*), and ash (*Fraxinus*). The *Thuja* was probably northern white cedar (*Thuja occidentalis*) and the *Tsuga* was most likely eastern hemlock (*Tsuga canadensis*). The nearest pollen record at Chippewa Bog (43.1°N, 83.2°W) contains some trace pollen evidence for *Tsuga* and *Cupressaceae* (probably including *Thuja*) between c. 6000 and 7100 $^{14}$C yr BP (Bailey and Ahearn, 1981, with data archived at National Climate Data Center, http://www.ncdc.noaa.gov/paleo/ftp-pollen.html). This highlights the importance of plant macrofossil finds such as Sanilac in broadening the picture of past regional vegetation distribution, i.e., based on pollen alone we might not have known of locally dense concentrations of *Thuja*–*Tsuga* on the regional landscape.

If our samples are assumed to be representative of the woody plant community at the time it was flooded, it would appear to be closest in community classification to rich conifer swamp (= cedar swamp; Michigan Natural Features Inventory [MNFI], Kost, 2002). This association indicates a relatively cool

Table 1
Samples collected from the Sanilac site during 1999–2001 and submitted for radiocarbon dating

| Sample no. | Field description | Portion dated | $^{14}$C age (yr BP ± 1s) | Cal age (yr BP) (2s Range) | $^{14}$C Lab no. |
|---|---|---|---|---|---|
| 1 | stump | rings 17–30 | 6805 ± 35 | 7640 (7690–7590) | A10571 |
| 2 | log | whole sect. | 6980 ± 60 | 7810 (7930–7690) | A10572 |
| 3 | stump | whole sect. | 6960 ± 55 | 7790 (7930–7680) | A11561 |
| 4 | stump fragment | whole sect. | 6780 ± 65 | 7630 (7750–7510) | A11562 |
| 5 | stump | rings 28–72 | 7095 ± 50 | 7920 (8010–7830) | A11563 |
| 6 | stump | rings 30–40 | 6620 ± 65 | 7510 (7600–7420) | A11564 |
| 7 | branch/trunk (29) | whole sect. | 6795 ± 65 | 7640 (7760–7520) | A12131 |
| 8 | branch/trunk (29) | whole sect. | 6640 ± 80 | 7520 (7660–7420) | A12132 |
| 9 | branch/root (29) | whole sect. | 6500 ± 75 | 7410 (7560–7270) | A12133 |
| 10 | branch/trunk (97) | whole sect. | 6815 ± 65 | 7660 (7790–7570) | A12153 |
| 11 | trunk/branch (97) | whole sect. | 6905 ± 75 | 7750 (7930–7610) | A12134 |
| 12 | branch/trunk (97) | whole sect. | 6715 ± 70 | 7580 (7680–7460) | A12136 |
| 13 | branch/trunk (77) | whole sect. | 6775 ± 65 | 7630 (7740–7510) | A12135 |
| 14 | trunk/branch (77) | whole sect. | 6700 ± 65 | 7570 (7670–7460) | A12154 |
| 15 | root (57) | whole sect. | 6780 ± 60 | 7630 (7730–7510) | A12155 |
| 16 | trunk/branch (57) | whole sect. | 6495 ± 50 | 7400 (7500–7290) | A12156 |
| 17 | root (57) | whole sect. | 7050 ± 55 | 7880 (7980–7750) | A12157 |
| 18 | trunk/branch (79) | whole sect. | 6895 ± 85 | 7740 (7930–7590) | A12137 |
| 19 | trunk/branch | none | – | – | – |
| 20 | stump | whole sect. | 6420 ± 70 | 7350 (7460–7180) | A12158 |

Measured conventional $^{14}$C age is given along with calibrated age (relative to AD 1950) and the 2 s calibrated age range rounded to the nearest 10 yr derived from the CALIB (version 5) program (Stuiver and Reimer, 1993; Reimer et al., 2004). Cell position in the grid is indicated in parentheses under field description (ref. Fig. 3).

Table 2
Species, tree-ring characteristics and isotopic composition of sample collection

| Sample number | Species | Cross-section | | | Number of rings | $\delta^{13}C$ [a] (‰) | $\delta^{18}O$ [b] (‰) |
|---|---|---|---|---|---|---|---|
| | | Area | Pith | Outer | | | |
| 1 | *Picea* | 0.5 disk | + | + | 158 | – | – |
| 2 | *Tsuga* | 0.3 disk | + | − | 129 | – | – |
| 3 | *Thuja* | 0.5 disk | − | − | n/a | −21.9 | – |
| 4 | *Thuja* | fragment | − | − | n/a | −23.0 | – |
| 5 | *Pinus strobus* | 0.5 disk | + | + | 126 | −24.9 | – |
| 6 | *Tsuga* | disk | + | + | 82 | −24.2 | – |
| 7 | *Tsuga* | 0.25 disk | − | − | 43 | −23.1 | 28.1 |
| 8 | *Thuja* | disk | + | − | n/a | −22.4 | 25.8 |
| 9 | *Thuja* | fragment | + | − | 18 | −22.0 | 27.1 |
| 10 | *Thuja* | fragment | − | − | c.10 | −22.2 | 27.4 |
| 11 | *Thuja* | fragment | − | + | 21 | −22.1 | 21.9 |
| 12 | Softwood | 0.5 disk | + | − | n/a | −24.5 | [15.0][b] |
| 13 | *Thuja* | 0.25 disk | + | + | 86 | −23.4 | [22.5][b] |
| 14 | *Thuja* | fragment | − | − | 72 | −20.8 | [26.9][b] |
| 15 | *Thuja* | fragment | − | − | c.20 | −20.8 | 28.9 |
| 16 | *Thuja* | fragment | − | − | 12 | −23.8 | [20.6][b] |
| 17 | White pine grp | 0.3 disk | + | − | 21 | −22.0 | 27.9 |
| 18 | *Tsuga* | disk | + | + | 212 | −24.2 | 29.0 |
| 19 | Hardwood | fragment | − | − | n/a | – | – |
| 20 | *Fraxinus* | 0.25 disk | − | + | 100 | −25.2 | [16.5][b] |

The presence (+) or absence (−) of innermost ("pith") and outermost growth rings inside the bark ("outer") is indicated. Under number of rings, "n/a" indicates tree-ring boundaries were not distinguishable on surfaces because of decay or compression.

[a] Most $\delta^{13}C$ values are an average of $\delta^{13}C$ measured to correct $^{14}C$ dates and a 2nd sub-sample submitted separately for $\delta^{13}C$ analysis.

[b] Discolored cellulose; results may be biased by oxygen from Fe-oxides.

groundwater-influenced wetland dominated by northern white cedar. Other common trees in such communities were represented in our samples, including spruce, hemlock, and white pine. The present distribution of rich conifer swamp in Michigan is primarily north of the climatic tension zone (transition zone where two forest community types meet and in which Sanilac County is located) in northern Lower Michigan and in Michigan's Upper Peninsula (Kost, 2002), the nearest border of which is 170 km north-northwest from Lexington, MI.

The present land area bordering Lake Huron around Lexington, MI is characterized by beech-sugar maple forest (MDNR), also called mesic northern forest (MNFI, Cohen, 2000). It differs from rich conifer swamp in being on moist to dry mesic sites mostly north of the tension zone. Although there are several species that can be dominants or co-dominants, white cedar is not among them, but it is a component of the canopy. The leading dominant of typical mesic northern forest is sugar maple (*Acer saccharum*). There is a conifer-dominated alternative among mesic northern forests but this has hemlock and yellow birch (*Betula alleghaniensis*) as the primary canopy components (Cohen, 2000). Because we found a clear dominance of northern white cedar and no sugar maple or birch in our samples, this indicates the present community type is different from what existed in the Sanilac site region some 7000 $^{14}C$ yr BP.

The compilation by Thompson et al. (1999) of climate associated with North American tree species allows us to specify climate conditions associated with a *Thuja* (*occidentalis*)–*Tsuga* (*canadensis*) forest. Within the field of climate overlap for these species, this forest would exist where mean January temperature falls between −15.9 and 3.0°C, mean July temperature falls between 14.1 and 25.0°C, and mean annual temperature falls between −0.6 and 12.4°C. The precipitation overlap indicates these species would coexist where January precipitation falls between 20 and 145 mm, July precipitation falls between 59 and 145 mm, and total annual precipitation falls between c. 700 and 1500 mm. For reference, the 100+ yr climate record at the Mt. Clemens meteorological station c. 80 km southwest of Lexington has mean January, July and annual temperatures of −4.5, 22.4, and 8.9°C, respectively, and mean January, July and annual total precipitation of 44.1, 76.6, and 727.6 mm, respectively (Williams et al., 2005). The analysis does not include *Pinus strobus*, whose range is similar to that of *Tsuga*, nor does it include *Fraxinus* (*americana*) and *Picea* (*mariana* and *glauca*), which have larger geographical ranges, but the common climate range in the analysis would again be controlled by *Thuja* and *Tsuga*.

## *Tree rings*

Ring counts for 15 of the 20 samples range from c. 10 in timber fragments to 212 rings in complete tree radii (Table 2). Samples excessively deteriorated or compressed prevented confident recognition of rings in 5 specimens.

Different tree species appeared to exhibit different degrees of wood preservation. The *Thuja* specimens seem to have survived mostly as fragments. In all cases *Thuja* wood was heavily damaged by decomposition and waterlogging with the exception of sample #13, which even had intact sapwood. *Tsuga* wood preservation varied from little trunk fragments to a complete stump with only partially missing sapwood. Both *Pinus strobus* and *Picea* exhibited good preservation in complete cross-sections (Table 2). Samples retaining a complete radius through cross-section had 82 to 212 rings. Total number of rings in the samples with complete radii varied with species (Fig. 4; Table 2). *Tsuga* achieved the longest lifespan among trees at the site (212 rings). *Thuja* and *Pinus* were the youngest trees (about 100 rings). Because the pith is missing, the age of *Fraxinus* is uncertain, but it might be c. 130–150 yr, which places *Fraxinus* in the intermediate age group with *Picea*.

## *Crossdating results*

Ring widths were measured on 8 samples (Table 2). Crossdating was possible only for tree-ring series from five samples (Fig. 5), each a different species, to produce 2 independent sequences with no missing rings. First, a 239-yr tree-ring sequence (floating tree-ring chronology) was obtained for the 212-yr series of #18 *Tsuga* and the 86-yr series of #13 *Thuja*. The 60-yr overlap between the matched series had a correlation coefficient of 0.35. Second, *Picea* (#1), *Pinus* (#5) and *Fraxinus* (#20) series crossdated over a 158-yr period with a 129-yr overlap. The mean correlation coefficient was 0.42. Correlations were significant for both sequences, but overlapping sequences derived from multiple species present uncertainties associated with their different physiologies, i.e.,

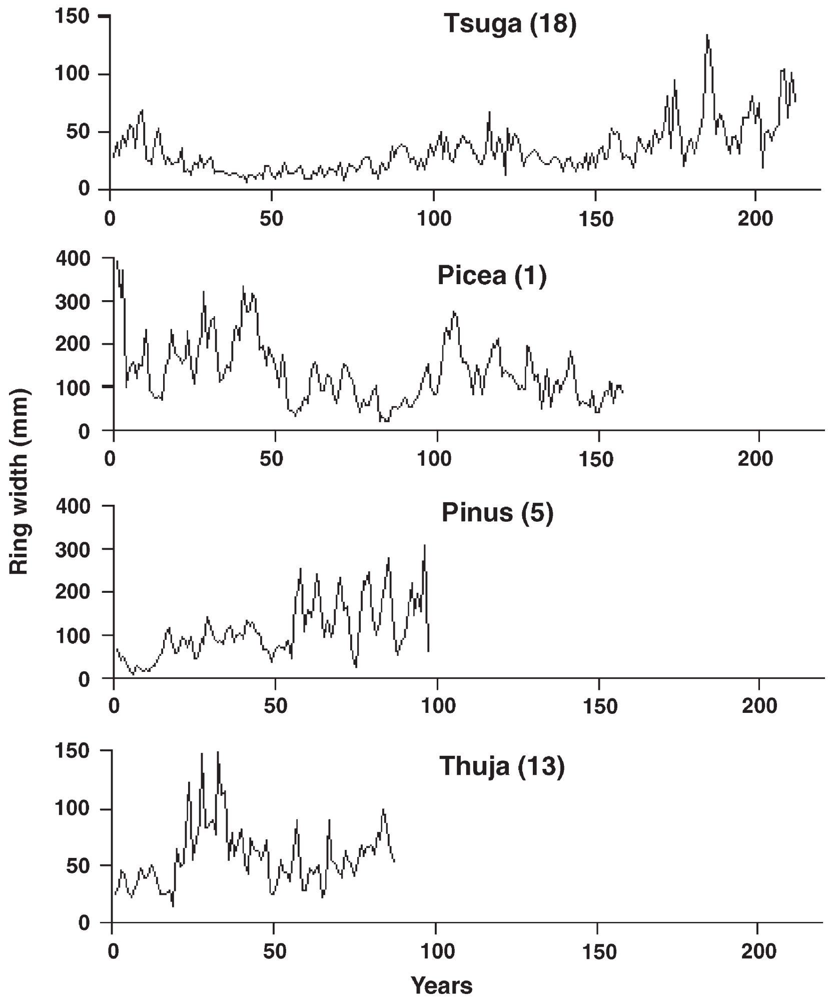


Figure 4. Examples of ring-width series of wood samples from the Sanilac site.

the crossdated sequences could overlap but do not crossdate because of different environment climate responses of the different species.

The tree-ring evidence therefore does not unequivocally indicate whether the trees in these two sequences coexisted. Unfortunately, the radiocarbon results cannot help resolve this question. On one hand, the radiocarbon ages of samples #13 and #18 (6775 and 6895 $^{14}$C yr BP; not statistically different) in the first tree-ring sequence overlap the second sequence ages of 6420, 6805, and 7095 $^{14}$C yr BP, which are all significantly different. If the crossdating is correct, then at least one of the radiocarbon ages (most likely #20, 6420 $^{14}$C yr BP) is erroneous. Our greatest confidence should be in stumps, because some of the log samples ("trunk/branch") may be driftwood associated with former lake stages. The radiocarbon age of stump #20 is suspect because it is so different from all the other stumps (#1—6805, #3—6960, #4—6780, #5—7095, #6—6620 $^{14}$C yr BP) that are consistent with a 400-yr forested interval.

*Environmental signals in ring widths*

The mean tree-ring widths (related to growth rate) appeared widely variable among species: *Thuja*—0.34, *Tsuga*—0.58, *Fraxinus*—0.80, *Pinus*—1.09, and *Picea*—1.33 mm (Figs. 4 and 5). *Picea* exhibits very rapid growth whereas *Thuja* grew slowly and produced very narrow rings. *Tsuga* displays two rates of growth. *Tsuga* sample #6 has 82 rings in an 18-cm diameter, while an 8-cm diameter *Tsuga* sample #18 contains 212 rings. Standard deviation of tree-ring width series also differed between the two crossdated groups (sequences). Standard deviations of series from samples #13 and #18 are 0.25 and 0.21, respectively, whereas standard deviations of series #1, 5, and 20 range from 0.49 to 0.7, which provides additional evidence that the two sequences are from different ages. Generally, the highly variable inter-annual ring widths suggest sensitivity of tree growth to environmental factors. First-order auto-correlation is high (from 0.61 to 0.78) in all series, suggesting tree-ring growth of the current year is highly dependent on growth condition of the previous year. Multi-decadal variability of each tree's crossdated series indicates complicated stand competition. *Fraxinus*, *Tsuga* and *Pinus* showed prolonged early periods of growth suppression (60–100 yr) in contrast to high early growth of *Picea* and *Thuja*, perhaps related to dominance of *Thuja* and *Picea*. The tree-ring series certainly contain environmental signals in their

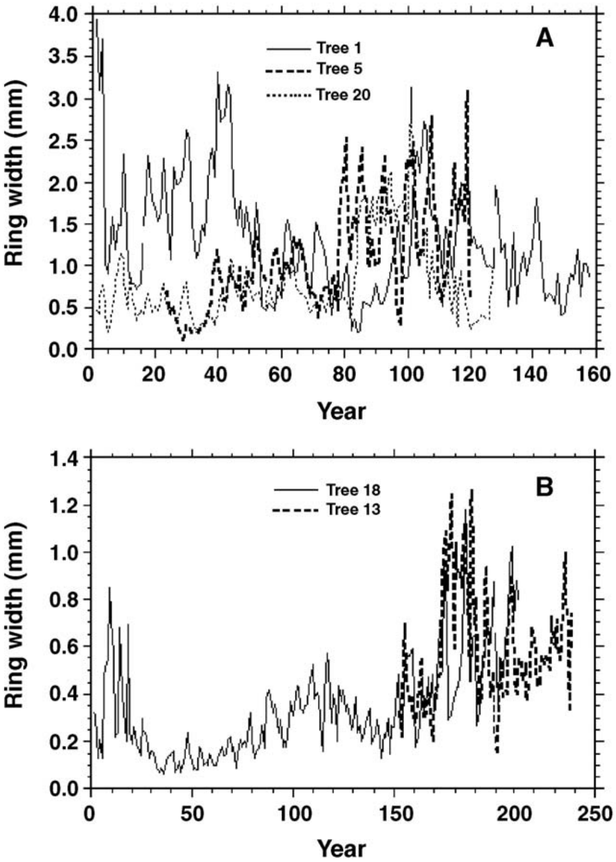


Figure 5. Two groups of crossdated ring-width series from wood samples at the Sanilac site. (A) *Picea* (sample #1), *Pinus* (#5), *Fraxinus* (#20); (B) *Thuja* (#13) and *Tsuga* (#18). Series A and B do not crossdate between themselves.

variability, likely forced by both climate and stand competition.

Overall, the tree rings suggest formation in a stressful environment with highly variable inter-annual weather conditions. All identified species prefer wet and cool growing conditions. Seedlings of almost every species are shade tolerant (except *Fraxinus*) and can survive in dense forests. Certain characteristics evidence wind interacting with unstable substrate. The *Fraxinus* specimen showed outside lobate growth form. Reaction wood, a response to tilting, was observed in all complete cross-sections and among all species. The rings do not clearly evidence death from drowning; for example, we did not observe any anomalies in wood anatomy of the rings that might be associated with flooding or oxygen deficiency in their roots (i.e., no outside ring-growth suppression or wounding). On the contrary, some trees showed remarkable 50-yr release (increased ring size) towards the end of their lifespan, which indicates improving growth conditions (Figs. 4 and 5). Buried trees in a Quebec boreal forest also support warmer climate in the mid-Holocene with faster growth rates and larger stems compared to the late Holocene (Arseneault and Sirois, 2004). Wind effects evidenced by reaction woods, could be consistent with death related to dune formation, but high growth rates could indicate local microenvironments on the landscape very favorable to growth.

### *Radiocarbon dating*

The radiocarbon ages ranged from 7095 ± 50 to 6420 ± 70 $^{14}C$ yr BP, corresponding to calibrated ages of c. 7920 to 7350 cal yr BP (Table 1). Twelve samples came from within the grid and 8 were outside it but in the same general area. Although dating of most specimens using their complete available cross-sections (pith to outer rings) helped ensure sufficient wood mass for conventional radiocarbon dating, the results represent average age for the specimen, which likely overestimates tree death ages by several decades for samples with many rings. For other samples with a few tens of rings (e.g., in Table 2 samples #9, 10, 11, 15, 16, 17, and possibly others for which rings were not identifiable), dating of the whole specimen caused no such age biasing. Where specific ring groups were subsampled for radiocarbon dating, their positions were noted (Table 1).

Based on the data presented in Tables 1 and 2, the oldest trees are pines (samples 5 and 17 at 7095 and 7050 $^{14}C$ yr BP) and the youngest is ash (sample 20 at 6420 $^{14}C$ yr BP). Both cedar (*Thuja*) and hemlock (*Tsuga*) range between these ages.

### *Wood stable-isotope composition*

The $\delta^{13}C$ values on holocellulose range from −20.8‰ to −25.2‰ (Table 2). *Thuja* tends to be the most $^{13}C$-enriched species (most positive average $\delta^{13}C$) but exhibited a wide range of values from −20.8 to −23.8‰. The only identified hardwood (#20 *Fraxinus*) at −25.2‰ was the most $^{13}C$-depleted species (most positive $\delta^{13}C$). Generally the conifer species were $^{13}C$-enriched to various degrees relative to the hardwood, although sample #5 *Pinus strobus* was very negative (−24.9‰). The $^{13}C$-depleted unidentifiable softwood (#12) seems most consistent with the *Pinus* and *Tsuga* samples.

The $\delta^{18}O$ values ranged from 15.0‰ to 29.0‰ (Table 2). Some of the $\delta^{18}O$ results may be biased by the presence of iron oxides, which could contaminate the oxygen liberated from the cellulose. The iron oxides may have been produced during chemical processing if disseminated pyrite was present in the samples derived from locally reducing conditions within the submerged wood. Disregarding those 5 questionable samples (marked in brackets in Table 2), $\delta^{18}O$ of the wood ranges from +21.9‰ to +29.0‰, with a mean of +26.7‰.

### *Comparison with modern trees and environment*

The $\delta^{13}C$ values on holocellulose from the Sanilac samples are similar to modern wood in temperate mid-latitudes of North America (e.g., Leavitt, 1993; 2002). The hardwood (*Fraxinus*) isotopic depletion in $^{13}C$ is consistent with observations in other studies (Stuiver and Braziunas, 1987). Plant $\delta^{13}C$ can be influenced by $\delta^{13}C$ of atmospheric $CO_2$, light, plant water-availability, nutrient availability, and temperature (Francey and Farquhar, 1982). The $\delta^{13}C$ of atmospheric $CO_2$ to which the Sanilac forest was exposed is within a few tenths ‰ of pre-industrial $\delta^{13}C$ values (Indermühle et al., 1999). Within *Thuja* alone, the range of −20.8‰ to −23.8‰ could indicate significant variability in the levels of light and/or moisture of forest microenvironments (i.e., −23.8‰ suggests lower light levels or higher moisture).

The $\delta^{18}O$ of photosynthates is dominated by the $\delta^{18}O$ of the water used in photosynthesis. The primary source is therefore precipitation, whose isotopic composition is dependent on temperature (causing seasonal and latitudinal differences), trajectory of air mass, rate of rainout from clouds, evaporation of raindrops below clouds and various other factors (e.g., Dansgaard, 1964; Gat, 1996), although some mixing with groundwater at the Sanilac site is suggested by the community association. Evaporation of water in the soil can further affect the isotopic composition of water taken up by the plant. Within the plant, evaporation through leaf stomata can enrich the leaf water in $^{18}O$ (higher $\delta^{18}O$) (Flanagan et al., 1991; Yakir, 1992). Furthermore, any isotopic enrichment signal imprinted upon photosynthates in the leaves by evaporated water might be at least partially reset back toward soil water isotopic composition during equilibration of transported photosynthetic products with xylem water in the trunk where the tree-ring cellulose is deposited (Roden et al., 2000).

The modern average isotopic composition of precipitation in the area of the Sanilac site is c. −10‰ to −12‰ based on isotopic composition of stream water (Kendall and Coplen, 2001). The current isotopic composition of Lake Huron water measured in the northern portion of the lake is c. −6.5‰ to −6.8‰ (Dettman et al., 1995), which contains contributions from both the Lake Huron watershed and water from Lake Superior and Lake Michigan. Estimates of lake water isotopic composition from $\delta^{18}O$ of fossil ostracodes suggest c. −14‰ to −22‰ between 10,000 and 9000 $^{14}C$ yr BP, −8‰ to −10‰ between 9000 and 8000 $^{14}C$ yr BP, and c. −22‰ at 7400 $^{14}C$ yr BP (Dettman et al., 1995), probably driven more by pulsed inputs of glacial melt water or episodic inflow from proglacial lakes such as Lake Agassiz than by major climate changes.

The Sanilac wood $\delta^{18}O$ can help constrain the isotopic composition of precipitation at the site c. 7600 cal yr BP. For example, if Sanilac had very high humidity during the growing season and evaporation effects were negligible, the maximum isotopic composition of precipitation could be estimated by subtracting the constant biochemical isotopic fractionation during photosynthesis, i.e., c. 27‰ (Yakir and DeNiro, 1990), from the isotopic composition of the wood. For the Sanilac wood averaging +27‰, the precipitation source water would therefore be close to 0‰. Even in moist sites, however, the average growing season relative humidity would realistically be less than 100%, evaporation effects would be important, and the isotopic composition of precipitation would be less than 0‰. A compilation by Edwards et al. (1985) of $\delta^{18}O$ of wood from modern trees at 11 sites over 30° of latitude in N. America, where relative humidity ranged from 54% to 72%, shows a gradient of cellulose $\delta^{18}O$ from +19‰ to +31‰ going from high latitude (61°N) to low latitude (32°N). The corresponding precipitation $\delta^{18}O$ shifted from −20‰ at high latitude to −4‰ at low latitude. Two of the sites are in Brampton and Ottawa, Ontario, similar in latitude but several hundred kilometers east of Sanilac, at which wood $\delta^{18}O$ was +24.6‰ and +24.4‰, in contrast to modern precipitation of −11.0‰ and −11.4‰, respectively (average growing season relative humidity of 64%). The Sanilac wood is c. 2‰ heavier than the modern wood, so if the relative humidity were the same 7600 yr ago, the precipitation would be about −9‰. A similar $\delta^{18}O$ difference between wood and precipitation is supported by modern spruce trees from the central Swiss plateau, where cellulose $\delta^{18}O$ was 28‰ to 30‰ in comparison to local growing-season rainfall of −7‰ to −10‰ (Anderson et al., 1998). If the Sanilac precipitation was −9‰, c. 1–3‰ greater than modern precipitation, warmer temperature than today could be implicated, although the floristic assemblage suggests “cool” wetland. Humidity lower than 64%, however, could produce the Sanilac cellulose values even if the precipitation $\delta^{18}O$ was the same as today. Given a Sanilac wetland environment, perhaps also close to the Lake Stanley shoreline, warmer temperatures are more likely than lower humidity.

### *Relation to other sites of the Stanley/Chippewa low*

In comparison to the rich conifer swamp at the Sanilac site, the wood from the submerged Olson site east of Chicago (150 m a.s.l.) was about 1000 yr older, with 7 stumps dated at 7820 to 8380 $^{14}C$ yr BP (c. 8600 to 9350 cal yr BP) (Chrzastowski et al., 1991). The Olson site supported a hardwood forest apparently dominated by oak (*Quercus*) and ash (*Fraxinus*).

Stumps at the Southport site (c. 178 m a.s.l.) near the shoreline in Kenosha County, WI (Fig. 1 site 2), gave a larger range of dates generally younger than the Sanilac forest (Schneider et al., 1979; Larsen, 1985; Leavitt, 1989), from about 4850 to 6350 $^{14}C$ yr BP (c. 5600 to 7270 cal yr BP). The Southport forest was mostly oak (*Quercus*), hickory (*Carya*), ash (*Fraxinus*), with some elm (*Ulmus*), maple (*Acer*), ironwood (*Ostrya*) and northern white cedar (*Thuja*) (Schneider et al., 1979; Leavitt, 1989). Although Larsen (1985) suggested the forest marked the entry of oak-hickory forests into southern Lake Michigan, the older and more southerly Olson site indicates oak was already established.

Wood samples from c. 140 m a.s.l. (36–37 m depth) at the Straits of Mackinac (Fig. 1 site 3) have been dated at 9780 ± 330 $^{14}C$ yr BP (11,200 cal yr BP, possibly spruce, *Picea*) (Crane and Griffin, 1970) and 8150 ± 300 $^{14}C$ yr BP (9060 cal yr BP, *Tsuga*) (Crane and Griffin, 1972). The overall macrofossil picture suggests that oak and the oak-hickory association entered the southern Lake Michigan basin around 8000 yr $^{14}C$ yr BP and remained. Oak and hickory dated at 6000 to 9000 yr $^{14}C$ yr BP is also reported at the Lincoln quarry site in central Illinois about 150 km south-southwest of the Olson site (Panyushkina et al., 2004). The Sanilac site is only about 75 km northward in latitude relative to Kenosha, but its cedar-hemlock forest established in the southern end of the Lake Huron basin about 7000 $^{14}C$ yr BP, suggests cooler, wetter conditions in southeastern Michigan than southeastern Wisconsin, although the previously cited pollen evidence suggests this forest association was not widespread in the region. The spruce/hemlock association in the Straits of Mackinac indicates similar cool/moist conditions persisted northward. Overall, the compositional pattern of Stanley/Chippewa-age forests seems to be generally similar to the modern gradient of associations.

*Implications for lake level history*

Radiocarbon dates from the Lake Huron basin and the St. Clair Delta to the south are summarized by Larsen (1987) and Lewis and Anderson (1989). These provide context for the Sanilac dates and the early Holocene history of the southern Huron Basin. The earliest evidence of sub-aerial exposure in the southern Huron basin is the occurrence of woody peat dated at 9370 $^{14}$C yr BP over glacio-lacustrine clay at 124 m a.s.l. (Fig. 1 site 7) with the pre-Nipissing transgression at the same locality indicated by algal gyttja dated at 8460 $^{14}$C yr BP (Lewis and Anderson, 1989). Figure 1 site 8 at 103 to 107 m a.s.l. indicates similar sub-aerial exposure for plant detritus and peat dated at 9350–8890 $^{14}$C yr BP (Lewis and Anderson, 1989). More recent dates obtained from the Sanilac site (Fig. 1 site 9) indicate the lake level was below 164 m between 7095 and 6420 $^{14}$C yr BP During that period, the Lewis and Anderson (1989) reconstruction for Lake Stanley indicates a rise from c. 144 to 160 m a.s.l. Our forest elevation is a good fit with that reconstruction, confirming inundation of land at 164 m a.s.l. c. 6420 $^{14}$C yr BP. Site 10 (Fig. 1) provides the timing of sub-aerial exposure (9310 $^{14}$C yr BP) and re-flooding of the St. Clair Delta at 172 m with rising water and flooding of marshes at 7300 $^{14}$C yr BP, followed by the establishment of the St. Clair River outlet and deltaic sedimentation by 6100 $^{14}$C yr BP (Mandelbaum, 1969; Larsen, 1987 and sources therein). Hence the Sanilac forest at 13 m below modern Lake Huron elevation, was flooded only 300–400 yr before Larsen's estimated re-establishment of drainage of Lake Huron to the south approximately 6100 $^{14}$C yr BP (Larsen, 1987).

Interestingly, 4 samples of wood (reportedly from stumps) were independently collected in 1991 in the vicinity of the Sanilac site in 13 m of water and submitted to C. Larsen of the U.S. Geological Survey (personal communication, August 2004) by Jim and Pat Stayer (Great Lakes Shipwreck Exploration Group, Lexington, MI). These samples dated from 7250 ± 110 (W-6339) to 7850 ± 150 (W-6340) $^{14}$C yr BP. If correct, these dates would expand the age of the wood from this forested site by about 700 yr, a sufficiently long period to support the hypothesis that tree death and burial in cedar swamp sediment or in sand by advancing dunes is likely to have occurred before inundation by rising lake level.

## Conclusions

We believe the Sanilac site is the largest reported aggregation of submerged Holocene tree remains in the modern Great Lakes. The cause of death of these trees is not known with certainty, but our multi-proxy analysis provides important results and constraints.

(1) The range of radiocarbon ages from c. 6420 to 7095 $^{14}$C yr BP suggests a long time period (c. 800 calibrated yr) represented by trees at the site. These dates establish that a rising Lake Huron had not yet re-opened the Port Huron/St. Clair River outlet before that time and agrees with literature estimates that such drainage occurred about 6100 $^{14}$C yr BP.
(2) The *Thuja–Tsuga*-dominated forest at the Sanilac site matches a modern community classification known as “rich conifer swamp” (a.k.a. “cedar swamp”), indicating the site was a relatively cool, groundwater-influenced wetland.
(3) Because *Thuja* and *Tsuga* pollen are only a trace component of nearby pollen records in the interval between 6000 and 7100 $^{14}$C yr BP, the Sanilac forest association must have been local in extent. Its existence, however, confirms the presence of this association, which might not have otherwise been identified in pollen records.
(4) Tree-ring widths show good sensitivity (inter-annual variability). The ring series do not show ring-width suppression due to $O_2$ deprivation of flooded root systems nor is it likely such a large collection of intact stumps and logs would remain in situ because of the considerable destructive and dispersive forces of typical shoreline processes such as wave erosion, ice action, and longshore drift. Whatever their cause of death, it is likely that wood preservation soon followed as a result of burial in silt or sand possibly facilitated by episodes of rising water levels.
(5) The range of $\delta^{13}$C values of bulk wood falls within the range reported for modern wood in this area, with *Thuja* being the most $^{13}$C-enriched of the Sanilac species. Comparison of $\delta^{18}$O in Sanilac wood versus that from modern wood implies the water used by the Sanilac trees (i.e., precipitation) had a value of c. −9‰, which is 1–3‰ heavier than modern precipitation in this area. Such heavier $\delta^{18}$O values in precipitation would be consistent with warmer temperatures than today.

This study evidences a rich conifer swamp at 164 m a.s.l. surviving no later than 6420 $^{14}$C yr BP, thereby establishing that a rising Lake Huron had not yet re-opened the Port Huron/St. Clair River outlet and agreeing with literature estimates that such drainage occurred about 6100 $^{14}$C yr BP.

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