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Tree-Ring Oxygen Isotope Values During the Last Glacial Maximum and Insights to Future Changes in Climate

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ABSTRACT

Annual tree-ring oxygen-isotope values were measured from sections of two fossil logs of *Picea mariana* (black spruce) recovered from last glacial maximum proglacial sediment in Illinois, USA. Collectively, the specimens date from ca. 25,130 to 24,720 cal years BP. Tree-ring oxygen-isotope spectral analysis series for both specimens revealed a 2–6 years periodicity. The Gulf of Mexico was the prominent moisture source during spring–summer growing seasons. Tree-ring oxygen-isotope based reconstruction of last glacial maximum precipitation suggests comparable values to modern El Niño Southern Oscillation-influenced meteoric water isotopes for the Midwest. Additional factors supporting El Niño Southern Oscillation-like late glacial maximum climate behaviour include the position of the perihelion and precession timing and a similar Earth-Sun distance.

1 | Introduction

El Niño Southern Oscillation (ENSO) is considered the main driver of the interannual climate variability on Earth with the ability to change global atmospheric circulation (Alizadeh 2023; Glaubke et al. 2024). Within the United States, modern precipitation responses to ENSO-driven phenomena are detectable throughout the country (Lee et al. 2023). Future impacts and behaviour of ENSO remain largely uncertain with the rapidly evolving changes in today's climate (IPCC 2021; Callahan and Mankin 2023; Liu et al. 2023). A better understanding of past ENSO-like climate behaviour may improve understanding of current and future ENSO patterns. El Niño (the warm trend) and La Niña (the cool trend) events are a quasi-oscillatory climate phenomenon of recurring 2–7 years temperature fluctuations between the ocean and atmosphere in the east-central equatorial Pacific Ocean (McPhaden et al. 2006; Cai et al. 2021, 2023). Recently, three extreme El Niño event years have occurred: 1982/1983, 1997/1998, and 2015/2016 (Santoso et al. 2017). Greater frequency and intensity of future ENSO events are predicted (Geng et al. 2022; Ying et al. 2022) with significant social and economic impacts.

Certain modern climate conditions are favourable for intensifying ENSO: (1) weakening of Pacific Walker cell circulation, (2) slowing of the Atlantic Meridional Overturning Circulation (AMOC), and related (3) southward shift of the Intertropical Convergence Zone (ITCZ) which is closely tied to the AMOC (Glaubke et al. 2024). General LGM climate conditions were similar to modern conditions (Hollstein et al. 2018; Tian and Jiang 2019; Koutavas et al. 2002; Chiang et al. 2003; Pöppelmeier et al. 2023; Yuan et al. 2023; Liu et al. 2024). The suspected ENSO-like behaviour and weakening of the Pacific Walker cell circulation during the LGM were tied to changes in the Earth's precession (Beaufort et al. 2001; Koutavas et al. 2002; Liu et al. 2024). Currently and during the late LGM, the perihelion occurs during the austral summer resulting in solar insolation maxima and minima during summer and winter months, respectively, creating extreme seasonal variation in solar irradiance for the southern hemisphere (Clement et al. 1999, 2000) and moderating seasonal variance for the northern hemisphere. Today, similar timing occurs with the perihelion occurring during January (2026) and the aphelion occurring during July (2026) (https://aa.usno.navy.mil/data/Earth_Seasons) resulting in a "distance effect" that may have significant implications for ENSO (Chiang et al. 2022; Chiang and Broccoli 2023) discussed below.

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Several recent publications have suggested a strong correlation between the conditions of the orbital precession and ENSO (e.g., Lu et al. 2019; Chiang et al. 2022; Chiang and Broccoli 2023; Beaufort and Sarr 2024; Yang, Liu, et al. 2025; Yang, Shi, et al. 2025). The position of the perihelion drives changes in the hydrologic cycle, and, therefore, changes in the $\delta^{18}O$ values of precipitation (Yang, Shi, et al. 2025; Boryczka et al. 2010) which are recorded in the source water for the tree-ring cellulose. The ENSO cycle, originating in the equatorial Pacific, is closely tied to the seasonal cycle of the Pacific cold tongue (region of cold surface waters stretching westward along the equator from the coast of South America). The annual cycle of the Pacific cold tongue is directly tied to the effect of Earth's axial tilt on the seasons and is recently postulated to be strongly influenced by a second annual cycle driven by the variation in Earth-Sun distance (distance effect) (Chiang et al. 2022; Chiang and Broccoli 2023). In particular, the tilt effect of Earth's orbital precession and associated distance effect cycle (22 kyr phase cycle) (similar conditions exist for the time of the LGM in this study and today concerning the winter perihelion and summer aphelion for the northern hemisphere) are postulated to have significant effects on the ENSO cycle (Lu et al. 2019; Chiang et al. 2022; Chiang and Broccoli 2023). The timing of the annual cycle of the distance effect is slightly longer than the tilt effect resulting in two cycles, orbital precession and the distance effect, going in and out of phase every 11,000 years (Chiang et al. 2022; Chiang and Broccoli 2023). Under current and LGM precession, the sun's intensity is greater during the austral summer of the perihelion.

Several studies have suggested that modern solar activity is similar to LGM activity, and climate conditions strongly influenced by solar forcing (e.g., Beaufort et al. 2001; Adolphi et al. 2014) further suggest orbital forcing associated with the precession cycle as a prominent mechanism in ENSO evolution. Changes in coupled ocean–atmosphere instability (e.g., Ekman upwelling current) is one of the main drivers of orbital forced ENSO intensity. Therefore, to better predict future climatic changes, it is crucial that we investigate the conditions that are associated with the LGM. Here we use the oxygen-isotope values of tree-ring cellulose from ancient trees that have been well preserved temporally and structurally for > 24,000 years, to examine changes during a window of the LGM. Most studies thus far have addressed these climate implications through extensive modelling studies. This study represents a rare data-driven approach utilizing oxygen isotopes preserved in ancient trees as climate recorders of the LGM.

2 | Geologic Setting

Two well-preserved *Picea mariana* (black spruce) logs were recovered at the base of a borrow pit from proglacial LGM laminated fine sand and silt in Morton, Illinois (40.600° N, −89.481° W). The remarkable wood preservation is attributed to its isolation and burial beneath approximately 25 m of dense, over-consolidated till. The last continental glaciers covered Illinois from about 31,000–16,000 cal years BP with the southernmost Lake Michigan lobe margin crossing the study area at 24,200 cal years BP (Curry and Petras 2011; Curry et al. 2018; Curry 2024). The study area during the LGM experienced a strong low-level thermal atmospheric gradient which persisted along the southern margin of the Laurentide Ice Sheet sustained by the cold ice sheet and relatively warm land surface. The thermal lows contributed to the formation of synoptic cyclones that tracked over the ice sheet along this margin fed by moisture from the Gulf of Mexico (Bromwich et al. 2005; Liu et al. 2010; Conroy et al. 2019). The condition of the LGM wood is intact and coherent (Supporting Information; Figures S1 and S2). Alpha-cellulose extracted from the spruce specimens is very resilient, and similar cellulose studies have been conducted using naturally preserved wood (e.g., Jahren and Sternberg 2002; Arosio et al. 2025).

3 | Methodology

Black spruce #1 (MS 1) has 189 visible rings, and black spruce #2 (MS 2) has 126 rings. In MS 1, 178 of the 189 annual rings were collected and analysed (interior rings 1–11 were too degraded), and in MS 2, 126 annual rings and pith were analysed. Accelerator mass spectrometry (AMS) radiocarbon ages were determined from pith and cambium for the two specimens (Table S3, Figure S3). For $\delta^{18}O$ analyses, α-cellulose extraction from whole wood used Soxhlet extraction methods (Green 1963; Leavitt and Danzer 1993; Loader et al. 1997) (see Supporting Information for more details). Oxygen-isotope analyses were performed at the Manitoba Isotope Research Facility, University of Manitoba, Winnipeg.

4 | Results

The mean calibrated radiocarbon ages of MS 1 and MS 2 pith to cambium samples do not overlap (25,130–24,490 cal years BP for MS 1; 24,830–24,720 cal years BP for MS 2). At sigma-1 level (68% confidence interval), 90 years of record may overlap (24950–24,860 cal years BP) (Table S3, Figure S3). For MS 1, the average $\delta^{18}O_{TR}$ value for rings 12–189 is +30.9‰ (±1.6‰) (Figure 1a). The maximum value of +35.7‰ occurred in ring 60 and the minimum value of +27.3‰ occurred in ring 155. A spectral analysis of oxygen isotopes over time (REDFIT Analysis; Schulz and Mudelsee 2002) of the $\delta^{18}O_{TR}$ values revealed significant periodicities above the 95% confidence level (CL) at 2–4.5 years (Figure 1b).

For MS 2, the average $\delta^{18}O_{TR}$ value for rings pith–126 is +30.2‰ (±1.0‰) (Figure 2a). The maximum value of +33.3‰ occurred in ring 42 and the minimum value of +28.1‰ occurred in rings 21 and 50. REDFIT analysis of the $\delta^{18}O_{TR}$ values revealed significant periodicities above the 95% CL at 2.9–6.1 years (Figure 2b). The periodicity at 84.7 years cannot be considered relevant since the span of the tree-ring time series is 126 years.

The source water oxygen isotopic composition ($\delta^{18}O_{SW}$) for the black spruce tree rings was reconstructed using the equation from Anderson et al. (2002) and the following parameter descriptions (additional details in Table S1),

$$\delta^{18}O_{SW} \approx \delta^{18}O_{TR} - (1-f)(1-h)\left(\varepsilon_e + \varepsilon_k\right) - \varepsilon_b$$

where $\delta^{18}O_{SW}$ is the oxygen isotope value of the source water, $\delta^{18}O_{TR}$ is the oxygen isotope values of the tree-ring, f represents the dampening factor, h is the relative humidity, ε_e is the equilibrium fractionation for water, ε_k is the kinetic fractionation against $H_2{}^{18}O$ compared to $H_2{}^{16}O$ during water vapour

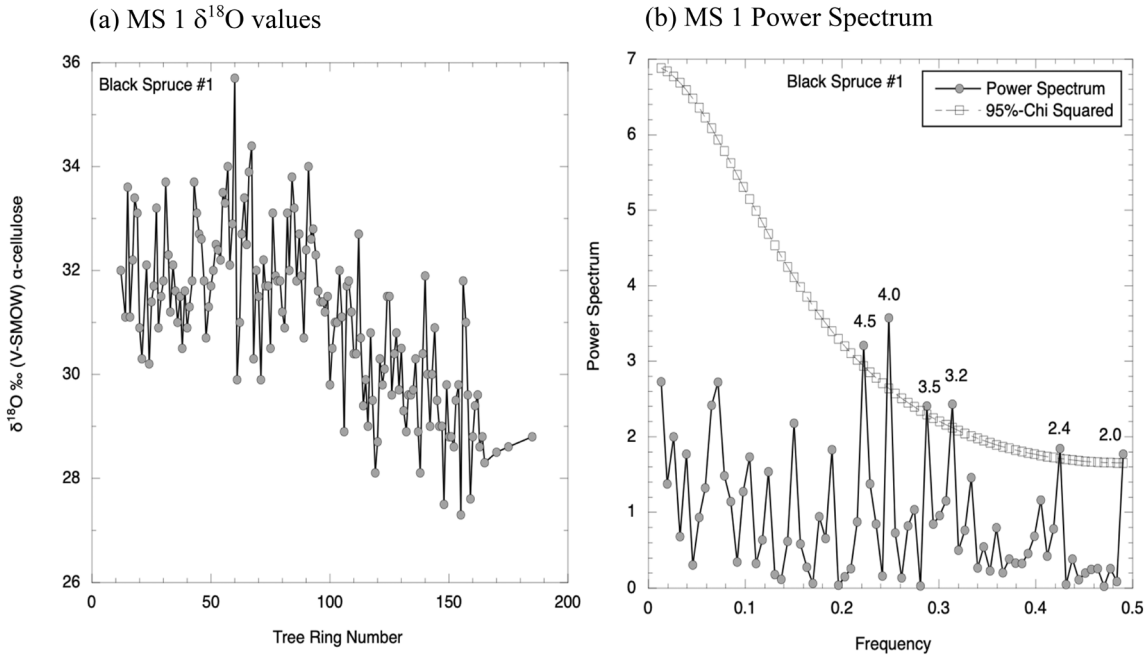


FIGURE 1 | (a, b) Annual oxygen isotope values for *Picea mariana*, MS 1, growing during the LGM (25,130 to 24,990 cal years BP) in the U.S. mid-continent (a). REDFIT analysis of the annual tree-ring oxygen values shows significant water source periodicities (1/frequency) between 2 and 4.5 years for MS 1 at the 95% CI and are labelled on the (b).

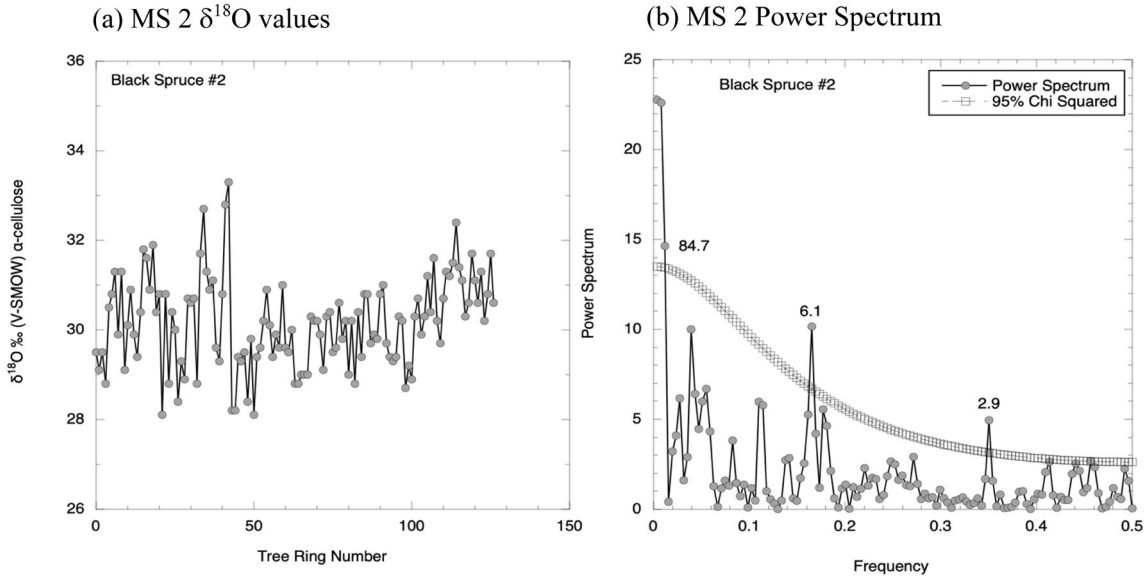


FIGURE 2 | (a, b) Annual oxygen isotope values for *Picea mariana*, MS 2, growing during the LGM (24,720 to 24,830 cal years BP) in the U.S. mid-continent (a). REDFIT analysis of the annual tree-ring oxygen values shows significant water source periodicities (1/frequency) between 2 and 6.1 years for MS 2 at the 95% CI and are labelled on the (b).

diffusion, and ε_b is the biochemical fractionation factor during cellulose synthesis between carbonyl oxygen molecules. Source water, $\delta^{18}O_{SW}$, values were calculated for temperatures between 2°C and 20°C. This range reasonably covers conditions during the LGM growing season since the global average surface temperature for North America during the LGM at ~40° N is estimated to be ~7°C (Otto-Bliesner and Brady 2006). Source-water isotope reconstruction was calculated using the $\delta^{18}O_{TR}$ value for each annual ring resulting in 290 annual source water, $\delta^{18}O_{SW}$, reconstructions. The annual average $\delta^{18}O_{SW}$ values for the calculated temperature range (2°C–20°C) for MS 1 is −6.2‰ and for MS 2 is −7.0‰ (Table S2).

5 | Discussion

Oxygen isotopes of tree-ring alpha cellulose, in particular black spruce trees, exhibit relatively steady correlations with

precipitation and maximal temperature over time (Naulier et al. 2015), and studies suggest that $\delta^{18}O$ value of tree rings is a good proxy for precipitation reconstructions (e.g., Brienen et al. 2012, 2013; Labotka et al. 2015; Klesse et al. 2018). The oxygen-isotope values of tree rings indicate that the main moisture source for these trees during the growing season was precipitation (e.g., Barbour et al. 2004). Glacial meltwater did not significantly influence source water isotopic compositions for glacial wood from Illinois during the LGM (Voelker et al. 2015). *Picea* have shallow root systems that are unlikely to tap groundwater (Anderson et al. 1998). No measurable oxygen-isotope fractionation occurs in source water as soil water is taken up into the xylem of roots, stems, and branches (Dawson and Ehleringer 1991, 1993).

The effects of ENSO directly impact the Midwest during the winter months. Although tree growth is dormant during the winter months, ENSO connections can significantly affect growing season conditions in the spring and early summer. Voelker et al. (2019) utilizing oxygen isotopes of modern white pines in Illinois near the Great Lakes region demonstrated that the spring and early summer $\delta^{18}O_{TR}$ values are linked to winter atmospheric circulation patterns directly influencing precipitation $\delta^{18}O$ values as well as indirectly via leaf water enrichment. Jong et al. (2020) and referenced studies have also linked complex ENSO teleconnections to Midwest spring/summer precipitation and temperature.

For both MS 1 and MS 2, the earlywood growth band dominates the annual growth ring suggesting the predominant growing season was during the late spring–early summer months and reflects these water sources accordingly. The reconstructed $\delta^{18}O_{SW}$ values of MS 1 (−6.2‰) and MS 2 (−7.0‰) are similar with the weighted mean average of precipitation measured at Chicago's Midway Airport between 1962 and 1978 with the value of −6.9‰ (Harvey 2001; Kay et al. 2002). The dominant moisture source of precipitation during the growing season then and now is the Gulf of Mexico.

(Bromwich et al. 2005; Liu et al. 2010). Sea level was about 120 m lower during the LGM (Lambeck et al. 2002), thus increasing the distance weather systems travelled over land and the rainout effect on precipitation. The continental ice sheets preferentially sequestered ^{16}O resulting in ocean water that was ~1‰ heavier in $\delta^{18}O$ than at present (Schrag et al. 2002). Voelker et al. (2015) argued that these effects resulted in oxygen-isotope precipitation values similar to those observed today despite the cooler conditions of the LGM. Biological proxies suggest LGM conditions were ~6°C cooler and received ~130 mm less precipitation in July (Curry and Delorme 2003; Nash et al. 2017; Curry and Anderson 2024). Potentially, less July precipitation may have affected the ring size of latewood growth.

Another notable isotope trend in MS 1 (Figure 1a) is a ~2‰ difference between rings 12–100 and 101–189. Around ring 100, the $\delta^{18}O_{TR}$ values exhibit a general trend toward more depleted values, although the multi-year variability appears to continue throughout the lifespan of the tree. This general trend is consistent for the last eight to nine decades of tree growth. The reasons for this trend are not well understood, but they may be related to changes in source water, such as a pulse of glacial meltwater reaching the Gulf of Mexico, providing a supply of ^{18}O-depleted water. Since the Bering Strait was largely closed during the LGM thereby cutting off meltwater flow into the Pacific Ocean (Pöppelmeier et al. 2023), an increased fresh meltwater discharge via the Mississippi River into the Gulf of Mexico is a distinct possibility. A pulse of meltwater may have temporarily altered the water source within the Gulf of Mexico toward more ^{16}O-enriched values, and the continuous downward trend in $\delta^{18}O_{TR}$ values is consistent with an initial and continuous input of meltwater into the Gulf of Mexico. As such, the isotopic trend toward lighter $\delta^{18}O_{TR}$ values may be due to this pulse, but the overall effects of climate influences such as ENSO-like influences were not ameliorated. The state of the AMOC would be affected by the input of fresh meltwater into the oceans, which in turn, would likely affect ENSO strength and variability. With the strength of the AMOC significantly weakened and substantially shallower during the LGM (e.g., Pöppelmeier et al. 2023), Liu et al. (2023) suggest strengthened ENSO behaviour due to overturning circulation slowdown allowing a reduction in the annual cycle of sea surface temperature and cross-equatorial winds in the eastern equatorial Pacific. A similar trend occurs in MS 2 with a notable abrupt change in $\delta^{18}O_{TR}$ values occurred at ring 42 to ring 43 where ~5‰ depletion in ^{18}O from ring 42 to ring 43 is observed (Figure 2a). Unlike the depletion trend noted in MS 1, the oxygen-isotope tree-ring series in MS 2 gradually trends toward more ^{18}O-enriched values.

Current examples of tree-ring oxygen isotopes capturing large-scale regional changes in the hydrologic cycle, and thus water source, include a study by Cintra et al. (2025) describing these effects in the Amazon. Other possibilities for the abrupt oxygen isotope depletion observed in both specimens include changes in precipitation or source water amount (wetter conditions), changes in evapotranspiration (increased relative humidity), and possible changes in precipitation source (e.g., Brienen et al. 2013). Both local and regional climate effects are applicable but not discernible with this limited dataset.

Several studies have suggested a link between the long-term behaviour of ENSO and precessional orbital variation (e.g., Clement et al. 1999, 2000; Beaufort et al. 2001; Koutavas et al. 2002; Schneider et al. 2014) with El Niño-like conditions dominating during the LGM (Zhang et al. 2021, 2022; Wang et al. 2022). Several studies have predicted the current warming climate will result in a weakening of the Hadley and Walker Cell circulation pattern which correlates with more extreme El Niño events (Vecchi and Soden 2007; Ma and Xie 2013; Ma et al. 2016; Santoso et al. 2017). Tanaka et al. (2004) have reported evidence for current upper tropospheric weakening of both the Hadley and Walker Cell and monsoon circulation patterns in recent decades. If we are experiencing a climatological state more suitable to ENSO conditions due to the current precessional orbital state, then will the impact of a warming climate exaggerate ENSO-like weather patterns? Current research suggests mixed possibilities. For example, a study by Ford et al. (2025) utilizes climate model comparisons of the Pliocene and today and suggest that the ocean's ability to absorb heat may have been underestimated while other studies suggest a strong correlation with more frequent and extreme ENSO events under current warming conditions (e.g., Thirumalai et al. 2024; Collazo et al. 2025).

Other modern climate oscillations occur on a similar ~2–6 years periodicity, and influences among climate interactions are rarely completely separable. For example, studies have revealed a correlation between modern ENSO and the quasi-biennial oscillation (QBO), an equatorial wind oscillation with a periodicity between 2 and 2.5 years (e.g., Richter et al. 2011; Hansen et al. 2016; Varotsos et al. 2018). ENSO is suspected to have a strong influence over the QBO which may impact wind patterns and, therefore, precipitation patterns. In addition, the strong correlation between ENSO and the Pacific Decadal Oscillation has known effects on precipitation patterns in the Midwest (Henson et al. 2017).

6 | Conclusion

The nearly three-century long combined record of annual tree-ring oxygen-isotope values from two *Picea* species growing during the LGM preserves a 2–6.1 years periodicity. This oxygen-isotope record is unique and supports several previous modelling climate studies that suggest parallels in complex ocean and atmosphere interconnections between the LGM and today and ENSO-like climate behaviour. Despite the cool glacial conditions, the 2–6.1 years periodicity in the $\delta^{18}O$ values of the tree rings examined in this study (Figures 1b and 2b) may be influenced by seasonal variations evolving from the extremes in solar irradiance noted in several studies (e.g., Clement et al. 1999, 2000; Lu et al. 2019; Chaing et al., 2022, 2023). Although the climate scenarios of the LGM and today exhibit significant differences, the similar oxygen isotope periodicities are possibly related to the position of the perihelion, timing of the precession, and the Earth-sun distance and their subsequent effects on ocean–atmosphere instability.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information with the online version of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** MS 1 black spruce tree section. **Figure S2:** MS 2 black spruce tree section. **Table S1:** Parameters for precipitation isotope reconstruction. **Table S2:** Measured tree-ring oxygen isotope values with corresponding modelled source water reconstruction values for MS 1 and MS 2. **Table S3:** Radiocarbon ages of MS 1 and MS 2 from the Getz Pit, Morton, IL (40.60023 N, −89.47992 W). Ages calibrated using Calib 8.2 (online; Stuiver and Reimer 1993) and IntCal 20 (Reimer et al. 2020). Samples ISGS 2047 and 2048 were determined using benzene scintillation methods, yielding much larger errors than the other samples with ages determined by Accelerator Mass Spectrometry. Results of ISGS 2047 are rejected. **Figure S3:** Radiocarbon age-dating range and overlap of two specimens.