Supplementary Material S1.

Site context, material provenance, and handling

Overview

This study analyses absolutely dated archaeological oak (*Quercus* spp.) from two sites in Nuremberg, southern Germany, selected because prior investigations identified heavily charred material at one site and waterlogged material at the other, and the findings were subsequently stored under different conditions after excavation. Both sites lie within the same regional setting and yielded fifteenth-century oak timbers suitable for the 1430–1444 CE ring window used for the tree-ring stable-isotope comparison. Summary metadata (sample codes, locality, storage, and ring spans) are listed in Table 1 (main text); full per-sample details in Table S1 (this supplementary material).

Imperial Castle "Deep Well" (dry-stored, thermally altered material)

Archaeological context

The "deep well" supplied water to the Imperial Castle in Nuremberg (Coordinates (WGS84): 49.4523° N, 11.0768° E). The well shaft—approximately 53 m deep—was sunk through Keuper sandstone to the level of the Pegnitz floodplain. Documentary sources mention the well from the 13th century onward. In 1563/1564, two superstructures were built above the shaft; both were destroyed during the bombing raids of 2 January 1945, and substantial fire debris fell into the shaft. Formerly air-dried wood within the debris absorbed water and sank, becoming waterlogged in situ.

Recovery, processing, and post-excavation storage

In 2012, underwater archaeological work recovered ~180 samples, with the larger components being charred oak beams. Immediately after retrieval, finds were wrapped in waterproof stretch film, transferred to the dendrochronology laboratory, unpacked and washed in cold, clean water (≈8–12 °C), and sawn into disc samples, then stored in deionised water. Nine oak beam fragments—representing the bulk of larger components—were dendrodated to the 15th century. Surfaces on most beams were severely fire-damaged; no waney edges or recognisable sapwood were preserved. Reported last-ring years for the broader set ranged 1434–1680 CE, with the most complete cross-sections ending between 1493 and 1497 CE.

After the 2012 examination, discs were air-dried in baker's racks to ~8% moisture content and archived dry at room temperature (loose/open polyethylene bags in numbered Euro stacking

containers). For the present isotope study, subsamples H054, H089, and H114 were taken from this dry-stored material and returned to the same dry archive after processing.

Relevance to grouping

Although originally waterlogged in situ, the deep-well timbers analysed here were dry-stored for years prior to isotopic analyses and are used to represent the thermal-alteration gradient: Unaffected (Un), Intact (In), Moderately charred (Mc), Fully charred (Fc).

Augustinerhof "Latrine" (waterlogged, wet-stored material)

Archaeological context

The Augustinerhof area (Coordinates (WGS84): 49.457846° N, 11.076098° E) occupies part of the Pegnitz floodplain. Earliest activity in the northwest dates to the 11th–12th centuries. In the late 12th–13th centuries, up to 0.5 m of loam was emplaced to raise/dry the ground for timber construction. After a brief abandonment before the mid-14th century, the area was reoccupied with additional infill and stone-founded buildings on timber pile foundations. Large-scale excavations in 2008 (ahead of hotel construction) recovered hundreds of wooden artefacts from wall foundations, latrines, and wells.

Recovery, processing, and post-excavation storage

Three oak boards from feature 1214 (latrine)—L0003, L0006, and L0007—were chosen; preservation was excellent (waterlogged oak within loam/clay). On site, samples were immediately wrapped in airtight stretch film, transported to the lab, cleaned in cold water (~8–12 °C), and sawn into slices; they were stored in deionised water.

Adjacent oak boards L0003–L0007 cross-dated with waney edge to 1517 CE. Compared with the deep-well material, examination was straightforward due to the high preservation quality.

After the 2008 examination, samples were cleaned in cold deionised water (≈6–8 °C) and sealed in PE bags. In 2023, material was reprocessed, cleaned again, and vacuum-sealed under nitrogen in transparent LDPE bags (150 µm). Throughout, samples were stored at constant humidity and 6–8 °C in the laboratory's waterlogged-sample archive (numbered Euro-stacking containers).

Relevance to grouping

These timbers remained wet-stored from recovery to analysis and represent the waterlogged and wet-stored set, sampled at two radial positions: outer surface (~0–1 mm) and centre (>20 mm from the surface).

Supplementary Table S1: Detailed sample metadata for archaeological oak material used in this study

LAB ID	***DC***	***Coordinates*** (UTM32; E,N)	***Location***	***Archive Box***	***Taxon***	***Sapwood Rings***	***TR***	***End***	***Arch. Project No.***	***Preservation / Analytical use***
NUER011_H054	NUER011	650449.2307 5480426.1449	Nuremberg tiefer Brunnen	K0187NS	QUE	n.d.	100	1495	M-2012-843-2_0	Charred around exterior; wet interior at recovery; used for thermal-alteration gradient
NUER011_H114	NUER011	650449.2307 5480426.1449	Nuremberg tiefer Brunnen	K0188NS	QUE	n.d.	73	1476	M-2012-843-2_0	Charred around exterior; wet interior at recovery; used for thermal-alteration gradient
NUER011_H089	NUER011	650449.2307 5480426.1449	Nuremberg tiefer Brunnen	K0188NS	QUE	n.d.	60	1454	M-2012-843-2_0	Charred around exterior; wet interior at recovery; used for thermal-alteration gradient
N08_L0004	NUER008	650410.6116 5479953.1605	Nuremberg Augustinerhof	K0072NS	QUE	17	102	1513	M-2008-622-1_0	Not charred, waterlogged; used for radial-position comparison
N08_L0007	NUER008	650410.6116 5479953.1605	Nuremberg Augustinerhof	K0072NS	QUE	19	94	1516	M-2008-622-1_0	Not charred, waterlogged; used for radial-position comparison
N08_L0006	NUER008	650410.6116 5479953.1605	Nuremberg Augustinerhof	K0072NS	QUE	21	90	1517	M-2008-622-1_0	Not charred, waterlogged; used for radial-position comparison

Notes: LAB ID = internal laboratory identification of the wood sample; DC = dendroarchaeological documentation code; QUE = *Quercus* spp.; n.d. = not determined; UTM32 = Universal Transverse Mercator zone 32 coordinates; TR = number of tree rings; End = last measured ring (CE). "Nuremberg tiefer Brunnen" refers to the Imperial Castle deep well, and "Nuremberg Augustinerhof" refers to the Augustinerhof excavation site. The isotope analyses used the common interval 1430–1444 CE extracted from these absolutely dated series.

Reference sources

Deep well:

- F. Huber, A. Baier, F. Elstner, H. Fricke, E. Heukeroth, C. Howe, U. Kleeberger und U. Kunz: Geologisch/archäologische Aufnahme des »Tiefen Brunnen« auf der Kaiserburg zu Nürnberg. Ein Beitrag zur Entstehungsgeschichte der Nürnberger Burganlagen. In: Geol. Blätter NO-Bayern 62, Heft 1-4, 2012, 11-48.
- F. Huber: Der Tiefe Brunnen von Nürnberg der Kaiserburg zu Nürnberg. In: Wetnotes, Ausgabe 10, 4. Quartal 2012, 86-91.
- F. Huber, A. Baier, H. Fricke, M. Nadler und J. Ulrich: Die Tauchuntersuchungen im »Tiefen Brunnen« der Kaiserburg zu Nürnberg. In: Florian Huber & Sunhild Kleingärtner: Gestrandet – Versenkt – Versunken: Faszination Unterwasserarchäologie, Neumünster 2014, 306-333.

Augustinerhof:

- J. Zeitler, F. Feuerhahn: Ein Stadtquartier aus dem 12. Jahrhundert – Ausgrabungen am Augustinerhof in Nürnberg. In: Das Archäologische Jahr in Bayern 2009, Stuttgart 2010, 122-125. (Preliminary report)

Supplementary Material S3.

Material and methods: laboratory procedures

Overview

This supplement details the laboratory procedures for holocellulose isolation and stable-isotope measurements ($\delta^{13}C$, $\delta^{18}O$). Dry-stored, thermally altered samples (Unaffected, Intact, Moderately charred, Fully charred) and wet-stored, waterlogged samples were processed identically, except that Fully charred (Fc) material did not yield extractable holocellulose. For Fc samples, bulk-wood $\delta^{13}C$ was measured only, whereas $\delta^{18}O$ was not determined.

Holocellulose extraction

Latewood from absolutely dated annual rings were dissected under a stereomicroscope and cut into small fragments with a scalpel. Holocellulose was extracted in F57 PTFE filter bags (Ankom Technology, Macedon, NY, USA) using a modified Jayme–Wise extraction protocol (Boettger et al., 2007) to remove extractives, non-structural carbohydrates, and lignin:

- Alkaline step: 5% NaOH, 2 × 2 h at 60 °C, to remove alkali-soluble components, including fatty acids, resins.
- Oxidative step: 7% $NaClO_2$, 30 h at 60 °C, buffered with acetic acid (99.8%) to maintain pH 4–5, for delignification.
- Rinsing and drying: samples were thoroughly rinsed three times in hot (~90 °C) distilled water, then drying at 50 °C for 24 h. Dried holocellulose was sealed in Eppendorf microtubes and stored in the dark at room temperature until analysis.

Stable isotope measurements (EA-IRMS)

Approximately 1 mg of holocellulose, or bulk wood for Fc rings, was weighed into tin (Sn) capsules for $\delta^{13}C$ analysis ($^{13}C/^{12}C$), and ~1 mg of holocellulose was weighed into silver (Ag) capsules for $\delta^{18}O$ analysis ($^{18}O/^{16}O$). Analyses were performed on a varioPYRO cube elemental analyser (Elementar Analysensysteme, Langenselbold, Germany) coupled in continuous-flow mode to an isotope ratio mass spectrometer ISOPRIME100 (Isoprime, Manchester, UK). For $\delta^{13}C$, samples were combusted to CO_2 at 960°C; for $\delta^{18}O$, samples were pyrolyzed to CO at 1450°C.

Isotope compositions are expressed in delta notation as $\delta^{n}X = R_{sample}/R_{standard} - 1$ (Coplen, 2011), where R_{sample} and $R_{standard}$ are the ratios of the heavy to light isotope of element X ($^{13}C/^{12}C$ or $^{18}O/^{16}O$) in the analysed sample and reference standard, respectively. Numerical values are

reported in per mil (‰) after multiplying $\delta^{n}X$ by 1000, relative to Vienna Pee Dee Belemnite (VPDB) for $\delta^{13}C$ and Vienna Standard Mean Ocean Water (VSMOW) for $\delta^{18}O$.

Quality control and isotope-scale normalisation

Prior to each analytical session, the mass spectrometer was tuned and tested for reference-gas stability (standard deviation ≤0.04‰ across ten pulses) and linearity (≤0.03‰/nA) over the expected ion current range of the samples (Urban et al., 2021). Measurement performance was verified using certified reference materials (caffeine, graphite, benzoic acids) and internal laboratory standards prepared from homogenised cellulose and wood powders. Standard deviations were below 0.03‰ for $\delta^{13}C$ and below 0.99‰ for $\delta^{18}O$ for international reference materials, and below 0.07‰ for $\delta^{13}C$ and below 0.64‰ for $\delta^{18}O$ for internal laboratory standards.

Measurement results were normalised and referenced to the international isotope scales using two-point scale normalisation based on certified reference materials from the International Atomic Energy Agency (IAEA) and the United States Geological Survey (USGS). Reference materials included IAEA-600 caffeine ($\delta^{13}C$ = -27.771‰) and USGS24 graphite ($\delta^{13}C$ = -16.049‰) for $\delta^{13}C$, and IAEA-601 benzoic acid ($\delta^{18}O$ = +23.14‰) and IAEA-602 benzoic acid ($\delta^{18}O$ = +71.28‰) for $\delta^{18}O$.

References

Boettger, T., et al. (2007). Wood cellulose preparation methods and mass spectrometric analyses of $\delta^{13}C$, $\delta^{18}O$, and non-exchangeable $\delta^{2}H$ values in cellulose, sugars, and starches. Rapid Communication in Mass Spectrometry, 21, 1442–1450.

Coplen, T.B. (2011). Guidelines and recommended terms for expression of stable-isotope-ratio and gas-ratio measurement results. Rapid Communications in Mass Spectrometry, 25(17), 2538–2560.

Urban, O., et al. (2021). The dendroclimatic value of oak stable isotopes. Dendrochronologia, 65, 125804.