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ISODATE – Software for stable isotope dendrochronology

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ABSTRACT

ISODATE is a complete dating package for stable oxygen isotope dendrochronology that offers a user-friendly workspace for processing, crossmatching and precisely dating stable isotope chronologies. ISODATE provides the first standardisation of approach for isotope laboratories and the heritage sector for dating and the reporting of dates. The software produces downloadable figures and CSV files containing series alignments and statistical results. The application is freely and publicly available online (isodate.swansea.ac.uk). A manual and guided example accompanies the software. It is hoped that community-led refinements and additional reference chronologies will be added to ISODATE as the technique develops and is adopted more widely.

1. Introduction

The application of stable isotopes in tree rings has been shown to be a versatile and effective method for precision dating (Davies et al., 2024; Haneca et al., 2025; Loader et al., 2021; McCarroll et al., 2019; Nakatsuka et al., 2020; Nayling et al., 2024; Sano et al., 2022, 2023, 2024; Shi et al., 2025). As the technique becomes more widely used there is a need to standardise its application and the reporting of dates. This is similar to the development of both ringwidth dendrochronology and radiocarbon dating (Baillie and Pilcher, 1973; Bronk Ramsey, 1995; Godwin, 1962; Historic England, 1998). But, unlike ringwidth dendrochronology and radiocarbon calibration, there is currently no publicly available software offering a standardised approach to isotope dendrochronology. As more laboratories develop isotope series for dating purposes, it is important that common protocols are established to ensure comparability and reproducibility. Recognising this need, we have developed the first freely available online software for stable isotope dendrochronology; ISODATE (isodate.swansea.ac.uk), which has been written in R (v4.4.2; R Core Team, 2024) using the 'shiny' package (Chang et al., 2024).

2. Overview of the statistical dating framework

The potential for using stable isotopes in precision dating has been recognised for many years (Leavitt et al., 1985; Roden, 2008), but it is only more recently that advances in sample preparation and mass spectrometry have made this a feasible and cost-effective dating technique. Loader et al. (2019) detail the development of an objective statistical framework for stable isotope dendrochronology. This framework is implemented in ISODATE and outlined here.

Dating through the simple correlation of raw tree-ring isotopic data is not appropriate due to the presence of meaningful low-frequency signals (i.e. long-term climatic variability) preserved within isotope data. Retaining the raw data could therefore influence the dating process by increasing the chance of errant dating, or inflating match statistics, where comparisons share a common low-frequency trend. Loader et al. (2019) found that for deciduous oak, a 9-year rectangular filter with indices calculated by subtraction provided the most parsimonious detrending solution; effectively removing longer-term trends without increasing autocorrelation in oxygen isotope series.

Similar to ringwidth dendrochronology, indexed sample data are then compared sequentially against a reference chronology with match statistics calculated for each position of overlap. For every comparison, the independent degrees of freedom are adjusted to account for autocorrelation (positive or negative) that remains after filtering, as well as for the loss of independence introduced by the filtering procedure. Correlation coefficients (r-values) are converted into Student's *t*-values using the number of independent degrees of freedom (not n-2), and the corresponding probability of error (expressed as 1/p) is corrected to take account of multiple testing using a Bonferroni procedure. Because of the asymptotic nature of the tails of the *t*-distributions, 1/p values are

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capped at one million. An Isolation Factor, calculated as the ratio of the first to second most probable match probabilities, provides an indication of the uniqueness of the best match. When the strongest match yields a $1/p < 100$ and/or the Isolation Factor is < 10, the sample is considered undated. When sample match statistics equal or exceed these thresholds, the potential date needs to be considered in the light of both the strength of the match, with the $1/p$ value providing a realistic estimate of the chances of the date being wrong, and independent evidence (e.g. historic records, sample context, expert knowledge).

3. ISODATE: basic operation and functionality

3.1. Access and data management

ISODATE can be accessed via the URL 'isodate.swansea.ac.uk' using a web-browser. Data are uploaded as individual or multiple series in CSV (comma separated values) file format. Each sample series has basic metadata (keycode, dating status and start/end dates) generated by ISODATE that can be accessed and edited. There is also an option to add user notes to sample metadata.

Sample series are loaded into one of three windows, named: Working, Reference and Archive. The Working window is intended for

Fig. 1. Example of the detailed results page between a sample of unknown age and the Loader et al. (2019) reference chronology.

samples that are actively being analysed, while the Reference window is for dated reference chronologies against which samples are compared. The Archive window is for storing samples during a session to maintain a clear workspace. Samples no longer needed can also be deleted from any of the windows.

3.2. Oxygen isotope dating

Here, the term crossmatching is used to describe the relative alignment of non-dated samples, while crossdating refers to the comparison of a non-dated test series against a dated sample, or a reference chronology, with a view to assigning a precise date. Two different algorithms are available. The 'Minimum Data Pairs' algorithm is designed for crossmatching samples with the aim of finding positions of alignment for chronology building. This method compares two series at all positions of overlap where there are at least 20 pairs of data. The 'Defined Period' algorithm is intended for crossdating. Here, there is an assumption that the true date falls within the period covered by the reference chronology. This algorithm only compares cases with full sample overlap and does not allow the test sample to run off the ends of the reference timeseries.

3.3. Crossmatching

The indexed series for comparison are selected from the workspace. Samples are compared using the 'Minimum Data Pairs' algorithm in a stepwise manner producing a set of match statistics for each potential alignment. For every comparison, ISODATE will report the strongest match between records. Where samples pass the objective criteria of Loader et al. (2019), ISODATE will highlight these for consideration.

3.4. Crossdating

Crossdating series follows a similar process to crossmatching, with the exception that non-dated series are compared against a dated series assigned as a reference. This process also uses the 'Defined Period Algorithm'. Once a sample has been dated securely, the sample metadata may be updated to assign calendar dates. Where a date is assigned to a series comprising multiple elements (i.e. a 'Composite' or 'Mean' record; see *Chronology Building* below) the end dates of the individual constituent series are also updated. ISODATE provides access to the Loader et al. (2019) reference chronology for Central England (1200–2000 CE) to crossdate against (Fig. 1), and it is hoped that with time additional standard chronologies will be added for community use.

3.5. Chronology building

ISODATE provides tools to build isotope chronologies as either 'Composite' or 'Mean' record types. Composite records are useful as a working tool for dating multiple samples from a single site using a list approach, where chronologies are aligned, dated and combined in a stepwise manner. Essentially, a Composite is two dimensional, it represents an average chronology which may be used for dating purposes, but it preserves a record of the individual samples used to calculate the Composite average at each step of its development. Composites can also be merged to calculate a new Composite record without having to restart the process. By contrast, a Mean record has a single dimension, it represents a single average chronology and may be considered the final step in the development of a tree, site or reference dataset.

When developing a chronology from multiple series for a single construction phase, site or as a regional reference chronology, both Mean and Composite series can be used together such that records may be combined without numerical (replication) bias relating to the number of sample series.

When constructing both Composites and Means, ISODATE keeps a record (viewable in the metadata) of the samples that are used to construct the series, and their start and end dates. The 'Samples Included', 'Components' and 'Construction' sections show how a chronology has been constructed. This is useful for tracing a record's construction.

3.6. Sharing outputs and saving the workspace

In addition to summary statistics, ISODATE also provides detailed interactive plots for all listed chronology comparisons. The graphical output permits users to visually compare the match for quality control and where multiple series are compared then a simple *t*-matrix can be produced. All graphical and numerical outputs can also be downloaded (300 dpi images or as raw data contained within CSV files; Fig. 2).

ISODATE is designed such that it is possible to save a project as an 'ISODATE' file. Once saved, the user can close the software returning later to upload the 'ISODATE' file and resume their analysis at the same point that the workspace was saved. It is also possible to share 'ISODATE' files with others in this way.

4. Manual and guided example

Included within the software is a detailed user manual, which can be accessed and downloaded from the 'Help' section. Additionally, a guided example to the use of ISODATE, with accompanying test data, are available as supplementary materials.

5. Discussion

The approach to isotope dendrochronology as described by Loader et al. (2019) is now regularly used to date samples across the United Kingdom (Davies et al., 2024; Loader et al., 2024; McCarroll et al., 2019) and is also being successfully applied more widely (Haneca et al., 2025; Nayling et al., 2023; Sano et al., 2022; Taïeb et al., 2024). Through ISODATE, it is now easier for dendrochronologists and stable isotope laboratories to compare and analyse their own data using a common statistical framework, meaning that results are directly comparable and more easily interpreted. It is hoped that ISODATE will remove a barrier to the wider uptake of stable oxygen isotope dendrochronology, allowing other regions to benefit from its ability to precisely date samples that are traditionally thought of as 'undatable'.

The authors envisage ISODATE as a community-driven project, with the opportunity to incorporate new regional reference chronologies into the software, making them publicly and freely accessible.

6. Conclusion

Stable oxygen isotope dendrochronology has had a significant impact on the scientific dating of historic buildings in the UK, enabling samples previously considered as 'undatable' to be securely dated. There is a growing number of teams successfully using stable isotopes for precision dating and with this comes a need for standardisation of approach and the reporting of dates. To support this and to aid the wider uptake and development of the technique, ISODATE provides a complete stable isotope dating package. With community input, it is hoped that ISODATE will provide a home for isotope dating that provides access to the dating tools and reference chronologies from across the globe that are required to advance this new dating technique.

CRediT authorship contribution statement

Danny McCarroll: Writing – review & editing, Software, Methodology, Conceptualization. **Neil J. Loader:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Darren Davies:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Conceptualization. **Christopher Bronk Ramsey:** Writing – review & editing, Methodology. **Dan**

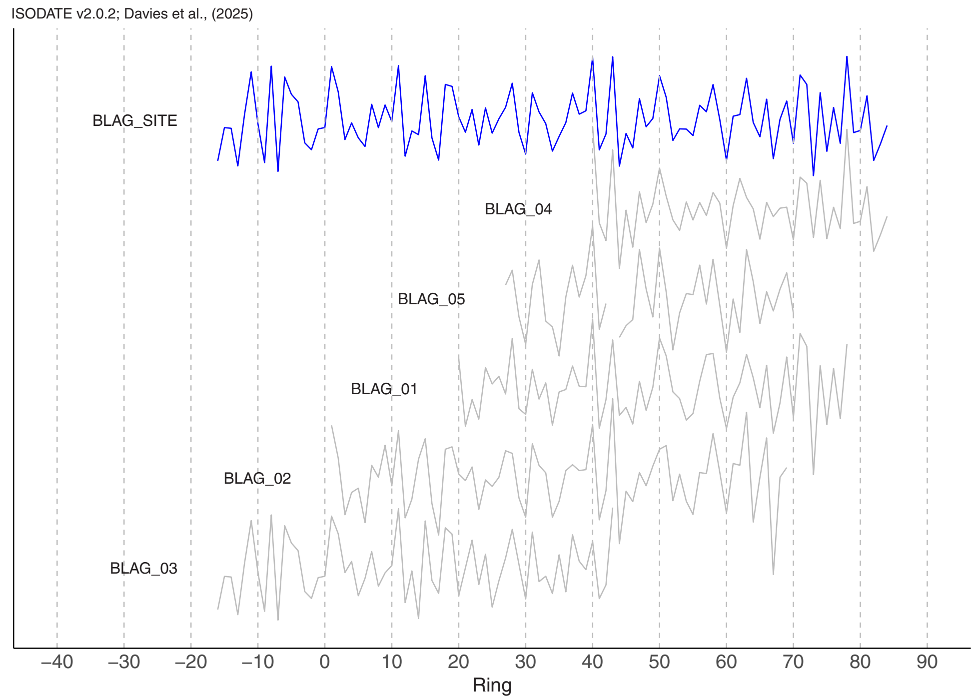

Fig. 2. Example of a 'Staggered Line Plot' downloaded from ISODATE, showing a Composite chronology (Blue) and its individual constituent samples (grey). The sample keycodes are also displayed.

Miles: Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2025.126385.

Data availability

Example stable oxygen isotope datasets have been made available as supplementary files.

References

Baillie, M.G.L., Pilcher, J.R., 1973. A simple crossdating program for tree-ring research. TreeRing Bull. 33, 7–14.

Bronk Ramsey, C., 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37 (2), 425–430. https://doi.org/10.1017/s0033822200030903.

Chang, W., Cheng, J., Allaire, J., Sievert, C., Schloerke, B., Xie, Y., Allen, J., McPherson, J., Dipert, A., Borges, B., 2024. shiny: Web Application Framework for R (1.10.0). Retrieved from ⟨https://CRAN.R-project.org/package=shiny⟩.

Davies, D., Mills, C.M., McCarroll, D., Loader, N.J., 2024. The precise and accurate dating of medieval bridge remains at Ancrum, Scottish Borders, using stable isotope dendrochronology. Journal Archaeological Science Reports 59. https://doi.org/10.1016/j.jasrep.2024.104753.

Godwin, H., 1962. Half-life of radiocarbon, 984-984 Nature 195. https://doi.org/10.1038/195984a0.

Haneca, K., Debonne, V., Davies, D., McCarroll, D., Loader, N.J., 2025. Oxygen isotope dendrochronology allows dating of historical timbers across a wide geographical region. Dendrochronologia 89. https://doi.org/10.1016/j.dendro.2024.126283.

Historic England, 1998. Guidelines on producing and interpreting dendrochronological dates. Hist. Engl. 1–39.

Leavitt, S.W., Long, A., Dean, J.S., 1985. Tree-ring dating through pattern-matching of stable-carbon isotope time series. TreeRing Bull. 45, 1–10.

Loader, N.J., McCarroll, D., Miles, D., Young, G.H.F., Davies, D., Bronk Ramsey, C., 2019. Tree ring dating using oxygen isotopes: a master chronology for central England. J. Quat. Sci. 34, 475–490. https://doi.org/10.1002/jqs.3115.

Loader, N.J., McCarroll, D., Miles, D., Young, G.H.F., Davies, D., Bronk Ramsey, C., Williams, M., Fudge, M., 2021. Dating of non-oak species in the United Kingdom historical buildings archive using stable oxygen isotopes. Dendrochronologia 69. https://doi.org/10.1016/j.dendro.2021.125862.

Loader, N.J., Davies, D., Miles, D., McCarroll, D., Bridge, M., Bale, R.J., 2024. Stable isotope tree-ring dates: list 5. Vernac. Archit. 1–4. https://doi.org/10.1080/03055477.2024.2427398.

McCarroll, D., Loader, N.J., Miles, D., Stanford, C., Suggett, R., Bronk Ramsey, C., Cook, R., Davies, D., Young, G.H.F., 2019. Oxygen isotope dendrochronology of Llwyn Celyn; one of the oldest houses in Wales. Dendrochronologia 58. https://doi.org/10.1016/j.dendro.2019.125653.

Nakatsuka, T., Sano, M., Li, Z., Xu, C., Tsushima, A., Shigeoka, Y., Sho, K., Ohnishi, K., Sakamoto, M., Ozaki, H., Higami, N., Nakao, N., Yokoyama, M., Mitsutani, T., 2020. A 2600-year summer climate reconstruction in central Japan by integrating tree-ring stable oxygen and hydrogen isotopes. Climate 16, 2153–2172. https://doi.org/10.5194/cp-16-2153-2020.

Nayling, N., Loader, N.J., Bale, R.J., Davies, D., McCarroll, D., Daux, V., 2023. Oxygen isotope dendrochronology of the newport medieval ship. Int. J. Naut. Archaeol. 53, 245–253. https://doi.org/10.1080/10572414.2023.2266473.

Nayling, N., Loader, N.J., Bale, R.J., Davies, D., McCarroll, D., Daux, V., 2024. Inter-genus oxygen isotope dendrochronology of the newport medieval ship keel. Int. J. Naut. Archaeol. 535–540. https://doi.org/10.1080/10572414.2024.2326985.

R Core Team, 2024. R: A Language and Environment for Statistical Computing. Vienna, Austria.

Roden, J., 2008. Cross-dating of tree ring $\delta^{18}O$ and $\delta^{13}C$ time series. Chem. Geol. 252, 72–79. https://doi.org/10.1016/j.chemgeo.2008.01.007.

Sano, M., Li, Z., Murakami, Y., Jinno, M., Ura, Y., Kaneda, A., Nakatsuka, T., 2022. Tree ring oxygen isotope dating of wood recovered from a canal in the ancient capital of Japan. J. Archaeolog. Sci. Rep. 45. https://doi.org/10.1016/j.jasrep.2022.103626.

Sano, M., Kimura, K., Miyake, F., Tokanai, F., Nakatsuka, T., 2023. Two new millennium-long tree-ring oxygen isotope chronologies (2349–1009 BCE and 1412–466 BCE) from Japan. Radiocarbon 65, 721–732. https://doi.org/10.1017/rdc.2023.29.
Sano, M., Li, Z., Tsushima, A., Kimura, K., Nakamura, T., Ohyama, M., Sakamoto, M., Nakatsuka, T., Hakozaki, M., 2024. A 1179-yr (417–1595 CE) tree-ring oxygen isotope chronology for northern Japan validated using the 774–775 CE radiocarbon spike. Radiocarbon 66, 485–497. https://doi.org/10.1017/rdc.2024.55.
Shi, S., Shi, J., Nakatsuka, T., Sano, M., Li, Z., Shu, J., Wang, X., Huang, J., Li, J., Lu, H., 2025. Tree-ring oxygen isotope cross-dating between southeastern China and central Japan. Dendrochronologia 91. https://doi.org/10.1016/j.dendro.2025.126319.
Taïeb, J., Daux, V., Alix, C., 2024. Dendroarchaeology of Birnirk and Thule architectural timbers (10–13th Centuries). Int. J. Wood Cult. 4, 17–38. https://doi.org/10.1163/27723194-bja10029.